U. S. DEPARTMENT OF THE INTERIOR
SMALL BUSINESS INNOVATION RESEARCH PROGRAM
PHASE I—FY 1983
PROJECT SUMMARY

Contract No. 14-12-0001-30116
Minerals Management Service
12203 Sunrise Valley Dr.,MS64
Reston, Virginia 22091

Attention:
Mr. F.M. Galinsky, Contracts Mgr.
Mr. C. Day, Contracting Officer
Mr. C.E. Smith, Contracting Officers Representative

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Program Office	TTM	Proposal No.	Topic No.

TO BE COMPLETED BY PROPOSER

Name and Address of ~~Proposer~~ Contractor

STARFIRE ENGINEERING, INC.
15603 KUYKENDAHL, SUITE 160
HOUSTON, TEXAS 77090

Name and Title of Principal Investigator

DR. D. BYNUM, JR., PRESIDENT

Title of Project

MINIMIZE MARINE PIPELINE OIL SPILL

Technical Abstract (Limit to two hundred words)

The scope of this Phase I research was to determine how environmental risks can be decreased and how the safety of personnel and property can be increased with offshore pipelines. This work shows how the objective can be achieved by a better material specification. When a marine pipeline is accidentally damaged by boat or ship anchor drag or by impact by fishermen trawl boards, the pipeline gets dented which can cause the line to collapse and then buckle with the buckle propagating down the line. In the process the line usually ruptures causing an oil spill or a gas leak. With a proper specification of the ultimate elongation of the steel, the pipe will stretch but not rupture during the collapse and buckling process.

Anticipated Results/Potential Commercial Applications of the Research

The Phase I results can be used now as rough guidelines. Phase 2 development work is needed to refine the procedures and for experimental confirmation of the theory. The anticipated results of the development work are that the oil, pipeline, and construction companies can use the procedures for improved steel pipe specification and DOI personnel can use the procedures for advice and counseling to industry. Implementation of the development work will result in safer pipelines and less environmental risk at no or negligible additional cost.

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* Numbers in parenthesis above indicate the number of charts applying to that section; all charts are placed at the end of the report for reader convenience.

INTRODUCTION

This project was a Phase I research effort performed through the SBIR (Small Business Innovative Research) Act passed by Congress and administered through the MMS (Minerals Management Service) in the U.S. Department of the Interior. The idea of SBIR is to get small business a little more involved in federally funded programs to expand our general technology base and to provide more jobs by commercial implementation. The program then consists of initial Phase I research efforts, a more comprehensive Phase 2 development effort by a few of the most viable participants in Phase 1, and then hopefully a Phase 3 commercial implementation without any federal funding.

The scope of this reported research was concerned with both environmental concern and personnel safety with offshore pipelines. These marine pipelines run between fixed offshore oil and gas production platforms and from the platforms to shore. The specific scope of this work was to ascertain considerations to minimize leaks in offshore pipelines.

We occasionally experience pipeline leaks due to a large variety of reasons as discussed in the next section. Fortunately, the number of leaks and amount of oil spilled is extremely small relative to amount of oil handled by marine pipelines. But we should strive to do better and make the efforts cost effective in the process. For example the cost of this research work is insignificant relative to the cost for cleaning up any one large oil spill.

Some of the major sources of marine pipeline leaks are damage by boats dragging anchor over a line or by fishing trawl boards banging the line. The resulting ding could initially rupture the line, or damage it so that it later fails when fully pressurized, or the protective coating could be damaged so that the line fails later by corrosion.

When an oil line leaks, it temporarily messes up the environment and is sometimes bad news for birds and fish - but virtually no danger to personnel will ensue. Conversely, with a gas line leak, there is no detectable damage to the environment, but if the line were near a platform, it is possible that this could lead to an explosion with significant loss of life and property.

Our approach here then is to figure out how that we can be reasonably sure that a damaged line will stretch but not rupture when it collapses. The way to do this is to first understand the geometry and mechanism of the failure mode of the pipe. Then we can predict the required elongation or stretch of the steel used in the pipeline.

We have done that in this report with the calculations shown for the preliminary theoretical procedures. The work shows that we should choose the type of steel for a particular pipeline based on internal operating pressure of the fluid being pumped, the external water pressure based on depth from the ocean level down to the mudline, and the pipe diameter and wall thickness.

It required some rather fancy engineering as outlined in this report to accomplish the objective. But the work was boiled down to a simple equation that can be used for steel mill specifications on a tentative basis. Experimental work will be required for verification and to improve the approximations.

Seems like the work discussed in this report should be of interest to various design engineers in several segments of industry such as oil and gas companies, marine pipeline construction companies, and the pipeline operating companies. More importantly this work will give MMS personnel a better understanding of pipeline failure mechanisms. With this additional knowledge MMS personnel should now be in a position to offer advice and counsel to industry during the review stages for new marine pipeline construction.

For the benefit of those readers that are not involved in marine pipeline work, a schematic of a barge depicting the system used to construct an offshore pipeline is shown in Chart 2-1. Drawing on our previous marine pipelay design work, the specifics for an example to show the influence of water depth is shown in Chart 2-1 with the results from the structural analyses shown in Chart 2-2.

OIL SPILL STATISTICS

From MMS data (Chart 3-1), there were 30 major spill incidents (greater than 238 bbl/incident) in the years 1964 through 1981 in the OCS Gulf of Mexico from all sources. In this time frame the number of offshore structures (platforms and satellites) increased from 1,100 to 2,744 (average 1,922) while annual oil production increased from 115 to 228 million bbl (359 peak in 1971) or accumulative 4,632 million bbl. These numbers equate to average 175 bbl spilled per structure and 13,791 barrels produced per bbl spilled.

In their very comprehensive treatise published Dec 77 on offshore pipeline safety practices, Funge et al (F5) collected extensive data on causes and volumes of oil spills. Their summaries are given in attached Charts 3-2 through 3-11 for the convenience of the reader with only the following brief comments. As an aside, extensive data is available from DOI and DOT for an update but the given information was considered sufficient for present purposes.

In all of the major accidents on the OCS involving 1,000 bbl or more spilled in the years 53-72, only four of the 43 total incidents were caused by pipeline ruptures but these four incidents accounted for over half of the oil spill volume (Chart 3-2). In the years 67-76, there were 22 pipeline spills of 50 bbl or more in OCS waters, one due to corrosion and six due to external impact of anchor drag, dredging or trawl boards (Chart 3-3). In the years 71-75 on the Gulf of Mexico OCS, oil spills of 50 bbl or less due to pipeline leaks and ruptures accounted for about 10% of the total number of spills and about 12% of the spill volume (Chart 3-6). The statistics on liquid pipeline spills onshore and offshore U.S. for the years 68-76 are given in Charts 3-9,10 with similar tabulations for gas pipelines in Chart 3-11.

CODES AND REGULATIONS

As shown by the most current Code of Federal Regulations (C1), the maximum design factor for offshore oil or gas pipelines is 0.72 based on SMYS, or a 1.4 safety factor. This also corresponds with the minimum safety factors specified in the various codes used in West European countries (P8), as shown by Chart 4-1.

The minimum test pressure is then taken as the sum of the external pressure plus 1.25 times the internal design pressure, IDP. The maximum internal pressure minus the minimum external pressure gives the internal design pressure. This API criteria (A14) is based on the ANSI piping standards (A8,9).

After a marine pipeline is installed and in operation it can incur damage due to several causes. Some areas in the Gulf of Mexico have big problems of soil fluidization and then transport with agitation by storm waves. Subsequent soil depressions leads to pipe bridging and the pipeline can then fail in fatigue because of the induced oscillations (H6).

In areas of heavy fishing activity the pipeline can become dented as trawl doors hit the line (G3). For this reason most offshore areas with fishing activities now have some type of pipeline burial requirement (M8), as shown in Chart 4-2.

At the present time neither DOT nor MMS have any regulations regarding allowable stress and strain during pipelay or repair operations. The applicable codes and regulations are concerned with adequate structural integrity of marine pipelines under stated normal operating conditions. As a consequence there are no codes or regulations that indicate desirable material property magnitudes to insure dry versus wet buckles or collapse.

DESIGN FOR OFFSHORE PIPELINE CONSTRUCTION

Some of the most important factors to be considered for laying offshore pipelines have been studied using a finite element program and these results were published in the literature (B5-B12). In another published study (B4) the available literature was reviewed and equations summarized for elastic hydrostatic collapse with and without out-of-round, plastic hydrostatic collapse pressure, and elastic buckling with combined loads. Design Chart 5-1 gives the maximum allowable bending moment as a function of water depth, and pipe diameter, wall thickness, and yield strength.

In a related paper (B22) the material properties as specified by the API Codes were summarized (Charts 5-2,3) for convenient reference during design. That paper also gave a number of other convenient design charts such as specific gravity for various sizes of pipe and concrete thickness, allowable water depths as a function of pressure, flexure, pipe dimensions, coating thickness, etc.

Haagsma (H8) reported some theoretical procedures to account for pipe out-of-roundness and to show the interaction between external pressure and either pure tension or bending. The essence of that work is given in Chart 5-4. This shows that the influence of out-of-round is greater for the lower D/t values, and that the allowable pressure is reduced more with pure line tension than with bending.

PIPE PROPERTIES

When trawl doors strike a marine pipeline for example, it would be more desirable that the pipe dent rather than crack. From this viewpoint a material with a higher toughness would be desirable. Charts 6-1,2 show the variation of charpy values reported by two manufacturers, Italsider (C6) and Kawasaki (U1), of API 5LXX70 pipe. Note that the charpy values increase with decreased sulfur content. While API specs give the minimum requirement for percent elongation in two inches, values of 36 to 44% have been reported in the literature (V1) for grades X65 and 70.

The design properties of API pipe are given in Charts 6-3,4. Pipe volumes are given in Chart 6-5.

PIPE COATINGS AND CATHODIC PROTECTION

Marine pipelines are normally protected with an organic coating in combination with cathodic protection. A concrete coating is then applied over the corrosion protection coating for weighting and stability purposes.

The six most often used corrosion protection coating materials are coal tar enamel, asphalt enamel, asphalt mastic, thin film powdered epoxy, bonded polyethylene, and various tape wraps. A survey of pipeline coatings was performed by O'Donnell (01) and his results are shown in Chart 7-1. This work shows that coal tar enamels are most often used. Adhesion was considered slightly more important than resistance to cathodic protection, and penetration resistance the third most important coating property. The tabulation of physical properties of pipeline coatings prepared by Askheim and Eliassen (A19) is given in Chart 7-2.

The current requirements and the capacity of anodes per NACE and discussed by Rizzo (R6) are given in Chart 7-3. Using DNV rules (Norway), Mollan and Eliassen (M9) reported a design procedure for spacing anodes on a marine pipeline and their technical data is given in Chart 7-4.

VALVES TO REDUCE OIL SPILL

When a marine pipeline fails it is possible for a buckle to propagate. Whether a wet buckle (pipe wall ruptures) or a dry buckle results depends upon the material properties of the pipe. As a contingency to minimize wet buckle oil spills, remote actuated valves have been installed in marine pipelines during pipelay operations. But sometimes a pipeline rolls as it is going over the stinger and the valve operator could be orientated upside down in the mud after being laid. In that case the valve could not be remotely closed.

If it is known sufficiently ahead of time that a very severe storm is going to pass through a pipeline lay barge location, the normal procedure is to abandon the pipeline. After the storm has passed the pipeline is retrieved and pipelay operations then continued. But this is an expensive operation. If the weather prediction is for a relatively mild storm, it may be decided to cease lay operations but to hang on to the pipe in the tensioners. This or relatively large vessel heave values can cause some small amount of plastic strain in the line due to dynamic flexure. Some weather design criteria for various offshore areas of the world are given in Chart 8-1.

As shown schematically in Chart 8-3 the reason that a pipeline will roll during lay operations is because the total energy of elastic and plastic strain in the pipeline is reduced with torsional rotation. The problem has been solved for a 60 ksi yield steel using the constructed stress strain diagram and the computed strain stress equations shown in Chart 8-2. Knowing the anticipated pipeline roll, the valve can then be placed in the joint at a prescribed angle so that it will be vertical when it reaches the mudline. An operations chart for this purpose is shown in Chart 8-3 for a 60 ksi steel.

NONLINEAR STRESS-STRAIN RELATIONS

An accurate prediction of pipeline collapse must take into account the nonlinear stress-strain relation of the steel in the plastic response after the yield strength has been exceeded. This behavior is peculiar to each type of steel and must be determined from uniaxial lab tests. A procedure and the results are given here for use in preliminary work when the actual mechanical properties of the steel being considered has not been tested. To do this we have utilized the reported tests by Brittain (B13) on a variety of different steels. Importantly, Brittain gave true rather than engineering values, and the essence of his work is summarized in Chart 9-1.

Most labs usually report their material property tests in terms of engineering values. Engineering stress is the force at any time during the test divided by the original cross sectional area of the test speciman. True stress is the applied force divided by the true necked down area at that time, so true stress is greater than engineering stress values in the plastic response. The true strain is the differential stretch divided by the instantaneous stretched length rather than the original length of speciman used to calculate engineering strain. Hence the true strain is less than the engineering strain in the plastic response. The equations for converting between true and engineering values as well as the definition of the strain hardening coefficient are given in Chart 9-2, and the significance of the differences is shown in Chart 9-4.

What we have done is mess around with the data in Chart 9-1 which is shown to be linear plots on log-log paper. Taking the standard equation functional for this type of relationship and the API definition of 0.5 percent strain at yield leads to the data points in Chart 9-3 for the constants K and n.

An example comparison is shown in Chart 9-4. The derived strain hardening coefficient using Ref. VI data is 0.15 versus 0.17 using our linearized coefficients shown in Chart 9-3.

ELASTOPLASTIC BEAM BEHAVIOR

To get to the problem of determining maximum strain in a pipe at collapse, we have to know a little bit about plastic structural analyses. In our first approximations we will also use beam theory. For the benefit of those engineers that do not perform plastic structural analyses every day, the basic theory for our procedures is given here.

Chart 10-1 gives the equations for various load types and beam end conditions for use in regular elastic analyses. When a sufficiently large moment is applied to exceed the yield strength, the beam moment versus curvature becomes nonlinear as the so-called plastic hinge point is formed as shown in Chart 10-2. The problem with all of the good textbook theory on plastic analyses is that the strain theoretically becomes infinite when the fully plastic moment has developed. That is no problem in ordinary structural analyses where the induced stresses are compared with allowable code stresses. But here we are interested in the strain values for use in material specifications and we cannot massage infinity.

Chart 10-3 gives the derivation of the fully plastic moment for a beam having a rectangular cross section. The results show that the fully plastic moment is 1.5 times the value of the maximum elastic moment. While the elastic moment varies nonlinearly along the beam length, Chart 10-4 shows that the moment varies linearly for all practical purposes from the point of maximum elastic load to the point of maximum plastic moment at the ends of a fixed end beam with uniformly distributed load. This is a key input to our collapse pressure derivation to get the maximum induced strain.

Chart 10-5 gives the derivation of the extent of plasticity at a hinge as a function of the beam curvature. These relations are required to study the intermediate stages of pipe collapse.

ELASTIC AND PLASTIC STRAIN ENERGY

The general three-dimensional equations of elasticity in rectangular coordinates are given in Chart 11-1. This includes the conversions between stress and strain using Young's modulus and Poisson's ratio for the three dimensional as well as the plane stress and plane strain cases.

The amount of internal energy stored in the structure (beam, shell, etc.) is called the strain energy. Chart 11-2 gives the total strain energy in terms of stress and in terms of strain for the general three dimensional stress state as well as for the case of plane stress.

The thing gets a little more complicated when the yield stress is exceeded. The strain energy is then the sum of the stored elastic energy plus the dissipated plastic energy. Chart 11-3 gives the equation of the plastic strain energy for a beam in terms of strain hardening coefficient of the material.

The resulting integral is not common. One way to solve the functional is to use a binomial expansion, multiply the terms, combine the units, then integrate each resulting integral in the sum of terms. The series of integrals is continued until the desired degree of accuracy is obtained, to wit, addition of remaining integrals beyond the truncation point would not significantly effect the results. This is not amenable to hand calculation but the problem could easily be handled with a computer when doing final design work.

VON MISES AND AISC FAILURE CRITERIA

The six commonly accepted bases of material failure are (1) maximum principal stress, (2) maximum shear stress, (3) maximum principal strain, (4) maximum shear strain, (5) total energy, (6) distortional energy. These failure modes are listed in order of ease of usage and hence engineering popularity. However, for structures under three dimensional stress, the precision and applicability would be given in reverse order.

The equations for the distortional energy basis, more commonly called the Von Mises criteria, for a triaxial stress state are given in Chart 12-1 in terms of stress and in terms of strain for elastic and plastic analyses. This shows that the equivalent uniaxial yield strain allowable is 33% greater in plasticity relative to an elastic state.

The pipeline considered in triaxial state versus biaxial stress is explained in Chart 12-2. This shows the allowable stress by Von Mises would be about 26% greater than permitted by the simplified ordinary analyses.

A laid section of pipeline is not free to expand longitudinally and the effect of this restraint is studied in Chart 12-3. Using the AISC Code procedures, the restraint would have negligible effect in contradistinction to the Von Mises approach.

COLLAPSE MODES AND PROPAGATION PRESSURE

When a pipeline has a dent in it or if the pipe is sufficiently out of round, then at a certain pressure the pipe will plastically deform radially inward and buckle longitudinally. If the pressure load is greater than the amount of stored elastic energy plus dissipated plastic energy, then the buckle will propagate along the length of the pipeline.

The amount of pressure to make the buckle propagate depends upon the failure mode. With a constant wall thickness along the pipe the collapsed state will look sort of like a figure 8. The derivation of an equation to predict the propagation pressure for an eight collapse is given in Chart 13-1.

If a pipeline is banded such as with a buckle arrestor ring, the pipe is then restrained from failing in the eight collapse. As the buckle propagates it then jumps through an unwelded arrestor ring in the collapse mode shown in Chart 13-2 and here called a nest collapse. As shown by the derivation in Chart 13-2, the propagation pressure for a nest collapse is approximately two times the propagation pressure for an eight collapse.

The various computed pressures for a couple of laid pipelines are shown in Chart 13-3 for examples. The computed pressures in psi for the first example were 223 due to external water pressure at the 500 foot depth, 920 for failure by external pressure, and 109 for a buckle propagation in an eight collapse mode. This means that if the pipe is sufficiently dented to cause a buckle in 500 feet of water, then without the use of buckle arrestors the buckle would progress along the length of the pipeline until a depth was reached where the propagation pressure is less than the water pressure, or to a water depth of 500 X 109/223 = 244 feet.

MAXIMUM STRAIN IN COLLAPSE MODE

It is now time to combine all of the previous information given to come up with something we can work with. The procedure is to equate the external work function with the internal strain energy. The elastic internal strain energy stored is very small compared to the plastic internal strain stored dissipated so we will neglect the elastic energy here. Chart 14-1 gives the relation for the external work after a complete figure eight collapse for one-fourth of the pipe.

Chart 14-2 gives the assumed strain variation at each quarter point or plastic hinge formed in the pipe after complete collapse. This strain functional is given in terms of the variation radially from the neutral axis and circumferentially from the hinge point. The functional is then integrated across each side of the equivalent beam at each end of a quarter section of the pipe with the results given in Chart 14-3.

The external work from Chart 14-1 is equated to the plastic strain energy from Chart 14-3 to obtain the relation of the expected maximum strain at the hinge as shown in Chart 14-4. Since the yield stress appears in both the work and the energy, this term drops out so the maximum strain is not a function of the yield strength. After the biaxial effects are taken into account using Von Mises strain criteria, the final result is that the maximum estimated strain at collapse is 12.75 divided by the pipe diameter to thickness ratio. Simple enough.

Using data from the published literature on a couple of laid pipelines, the first shows a 30.7% strain requirement and the second shows a 62.5% strain requirement. These are the ultimate strain values the material should have as determined by a uniaxial tensile test so that the installed pipeline completely failed in a figure eight collapse will have stretched without rupture.

BUCKLE PROPAGATION AND ARRESTORS

The ratio of critical pressure for collapse due to external pressure on a round pipe compared to the buckle propagation pressure is discussed in equation form in Charts 15-1,2. This shows why a buckle in a pipeline will propagate until much more shallow water depth is reached or until the buckle runs into a thicker section such as at a buckle arrestor or a line valve.

In practice the critical/propagation ratios are lower than the theoretical predictions because the formulas are for perfectly round pipe. Some out-of-roundness is allowed for the steel mill per ASTM and AISC codes since it is not practical or even possible to find <u>perfectly</u> round pipe.

The pipe buckles and the buckle propagates because of gross out-of-round or a ding due to unplanned damage to the pipe as previously discussed. The radial velocity of the buckle propagation is a function of the pressure head, i.e. the difference between the external water pressure and the propagation pressure as illustrated in Chart 15-3. The longitudinal velocity of the buckle propagation is a function of the yield stress, pipe diameter, and pipe wall thickness. The buckle shape will find a configuration for minimum plastic strain energy per unit length of additional deformation.

The size and type of buckle arrestor ring to use depends upon technical and economic considerations. Normally, a welded arrestor is better than a grouted arrestor since the buckle can jump through the grouted arrestor as shown in Chart 15-4. However, grouted arrestors would be appropriate if the jump through pressure exceeded the external water pressure, i.e. for the case of very shallow water depths.

CONCLUSIONS

1. This project was concerned with both pipeline safety and environmental considerations by decreasing the possibilities of offshore pipeline leaks as a result of damage to the laid line due to anchor drag, dings by fishermen trawl boards, etc.

2. The approach was to determine a suitable minimum mechanical property specification, to wit, ultimate elongation, so that a damaged pipeline could collapse and in the process, stretch but not rupture.

3. If the pipeline does not rupture at collapse, this will preclude oil spills and consequential damage to the birds, the fish, and the beaches. For the case of gas pipelines where failure has inconsequential environmental effects, a collapsed gas line without rupture near an offshore platform or terminal facilities greatly improves the safety for people and property.

4. Using some simplified assumptions in this Phase I work, the results were that the minimum ultimate elongation as determined from a uniaxial tensile test on the material to be used in a planned pipeline should be equal or greater than about 12.7 divided by the diameter to thickness ratio of the pipe.

5. The greater the strain hardening coefficient of a candidate steel, the more the determined minimum ultimate elongation can be decreased as long as the Charpy or Izod values are not adversely affected.

6. The results given in this report can be used as guidelines now. Before implementing the results into a final specification or technical requirement, the approach should be refined by including the effect of the strain hardening coefficient, etc.

RECOMMENDATIONS

1. Laboratory tests should be performed to confirm the theory presented in this report.

2. To reduce the cost of the lab tests, this should be done primarily with line loads applied to sections of pipe with only a few of the more expensive tests performed using external pressure loading.

3. Similar theoretical treatment of line load application will be required to confirm the theoretical line load/pressure load analog, the experimental line load/pressure load analog, and finally the theoretical pressure load/experimental line load analog.

4. The required ultimate elongation properties should be discussed with personnel in the metallurgical labs of several steel pipe companies to ascertain whether or not they have a steel chemistry formulation that has the desirable characteristics and which can be produced at negligible additional cost.

5. Complete mechanical property evaluations and test results should be obtained from the steel mills, including minimum yield strength, maximum tensile strength, ultimate elongation, strain hardening coefficient, and charpy results for candidate steel comparisons.

6. Equations should be developed for determining the conditions of suitability of the less expensive type of grouted buckle arrestors.

7. Equations should be developed for determining the economics and cost effectiveness of both grouted and welded buckle arrestors.

8. The above should be performed with the <u>objective</u> of improving safety to personnel and property as well as achieving decreased risk of environmental damage at minimum or no additional costs by working smarter with a better technology base.

NOMENCLATURE

Symbol	Variable	Typical Units
A	area	sq. in.
c	one-half of pipe wall thickness	in.
D	pipe diameter	in.
E	Young's modulus of elasticity	psi
g	gravitational constant	ft./sec.^{2}
H	water depth	ft.
h	arrestor wall thickness	in.
I	area moment of inertia	in.^{4}
L	length of pipe secant	in.
M	moment	in.-lb.
n	strain hardening coefficient	numeric
P	pressure	psi
R	radius of curvature	in.
t	pipe wall thickness	in.
V	volume	cu. in.
v	velocity	in./sec.
W	external work	in.-lb.
x	radial coordinate	in.
y	circumferential coordinate	in.
Z	area section modulus	in.^{3}
β	propagating buckle angle	deg.
μ	Poisson's ratio	numeric
σ	stress	psi
γ	density of material	pcf
ε	strain	in./in.
$\mathcal{E}$	internal strain energy	in.-lb.

Subscripts

a	arrestor	i	initiation	R	radial
c	critical	L	longitudinal	u	ultimate
d	dissipated	N	nest propagation	w	water
e	external	P	propagation	y	yield

LIST OF ABBREVIATIONS

AIAA	American Institute for Aeronautics and Aerospace Journal
AIMMPE	American Institute of Mining, Metallurgical, and Petroleum Engineers
AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
CAS	Computers and Structures (Pergamon Press, UK)
DNV	Det Norske Veritas
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
EM	Experimental Mechanics
EMD	Engineering Mechanics Division (ASCE)
GPO	U.S. Government Printing Office
IJPVP	International Journal for Pressure Vessels and Piping
IJSS	International Journal of Solid Structures (Pergamon Press Ltd., UK)
JAM	Journal of Applied Mechanics (Trans. ASME)
JAS	Journal of the Aerospace Sciences
JEI	Journal of Engineering for Industry (Trans. ASME)
JEMT	Journal of Engineering Materials and Technology (Trans. ASME)
JERT	Journal of Energy Resources Technology (Trans. ASME)
JMES	Journal of Mechanical Engineering Science
JPT	Journal of Petroleum Technology (SPE)
JPVT	Journal of Pressure Vessel Technology (Trans. ASME)
JSD	Journal of the Structural Division (Trans. ASCE)

MCET	Mechanical and Chemical Engineering Transactions, Inst. of Engineers, Australia
MMS	Minerals Management Service (DOI)
MT	Marine Technology
N	Number
NACE	National Association of Corrosion Engineers
NSC	Nippon Steel Corp., Kanagawa, Japan
NTIS	National Technical Information Services
NYAS	Transactions of New York Academy of Sciences
OCS	Outer Continental Shelf
OE	Ocean Engineering (Pergamon Press Ltd., UK)
OEM	Ocean Engineering Magazine
OGJ	Oil and Gas Journal
OI	Ocean Industry
OM	Offshore Magazine
OTC	Offshore Technology Conference (held annually first week in May in Houston, Texas)
PD	Petroleum Division (ASME)
PE	Petroleum Engineer
PGJ	Pipeline and Gas Journal
PLI	Pipe Line Industry
PRADS	International Symposium on Practical Design in Shipbuilding
PT	Petroleum Times
PVPD	Pressure Vessel and Piping Division (ASME)
p	Page
QAM	Quarterly of Applied Mathematics
SMI	Sumitomo Metal Industries Ltd., Osaka, Japan
SMYS	Specified Minimum Yield Strength

SPE	Society of Petroleum Engineers
V	Volume
WRC	Welding Research Council
ZAMM	Zeitschrift fur Angewandte Mathematek und Mechanik

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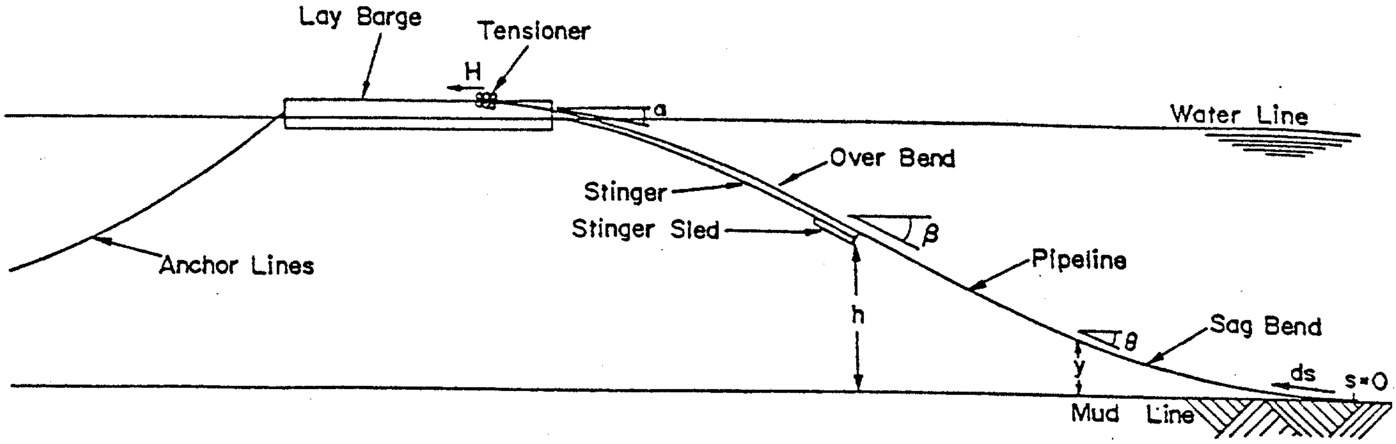
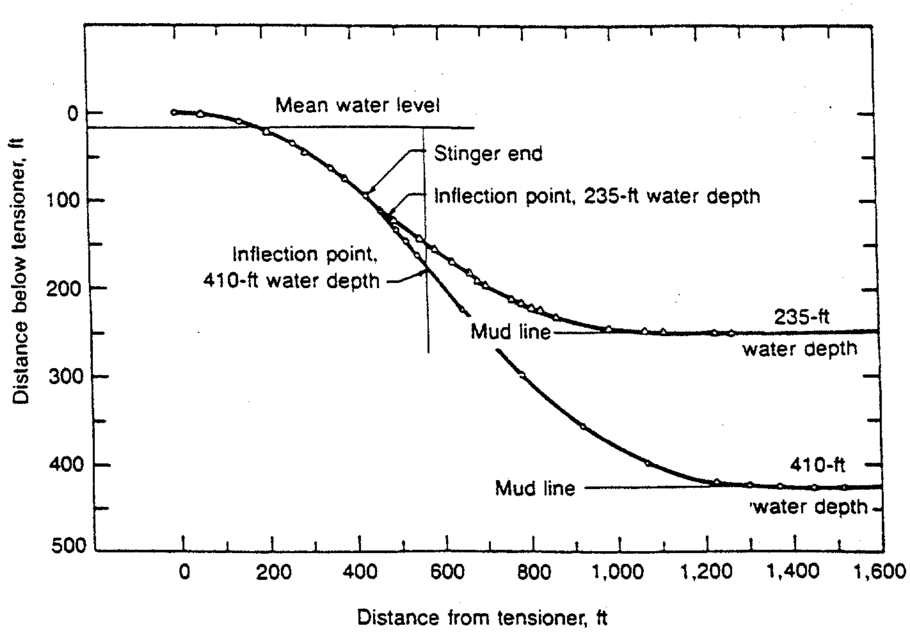
MARINE PIPELAY—SCHEMATIC AND EXAMPLE VARIABLES

CHART 2-1



Variables for water depth

234 and 410 ft	Water depth from mean water level to mud line
120 and 124 kips	Barge tension
15 ft	Distance from tensioner to mean waterline
1,000 ft	Curved stinger radius
36 in.	Pipe outside diameter
0.75 in.	Pipe wall thickness
3.5 in.	Pipe coating thickness
734 lb/ft	Weight of coated pipeline in air
89.3 lb/ft	Weight of coated pipeline in water
7.66	Specific gravity of steel
2.33	Specific gravity of coating
3.45	Specific gravity of coated pipeline in air
1.17	Specific gravity of coated pipeline in water
30×10^3 ksi	Young's modulus of the pipe
0.3	Poisson's ratio of the pipe
50 ksi	Allowable stress in the pipe

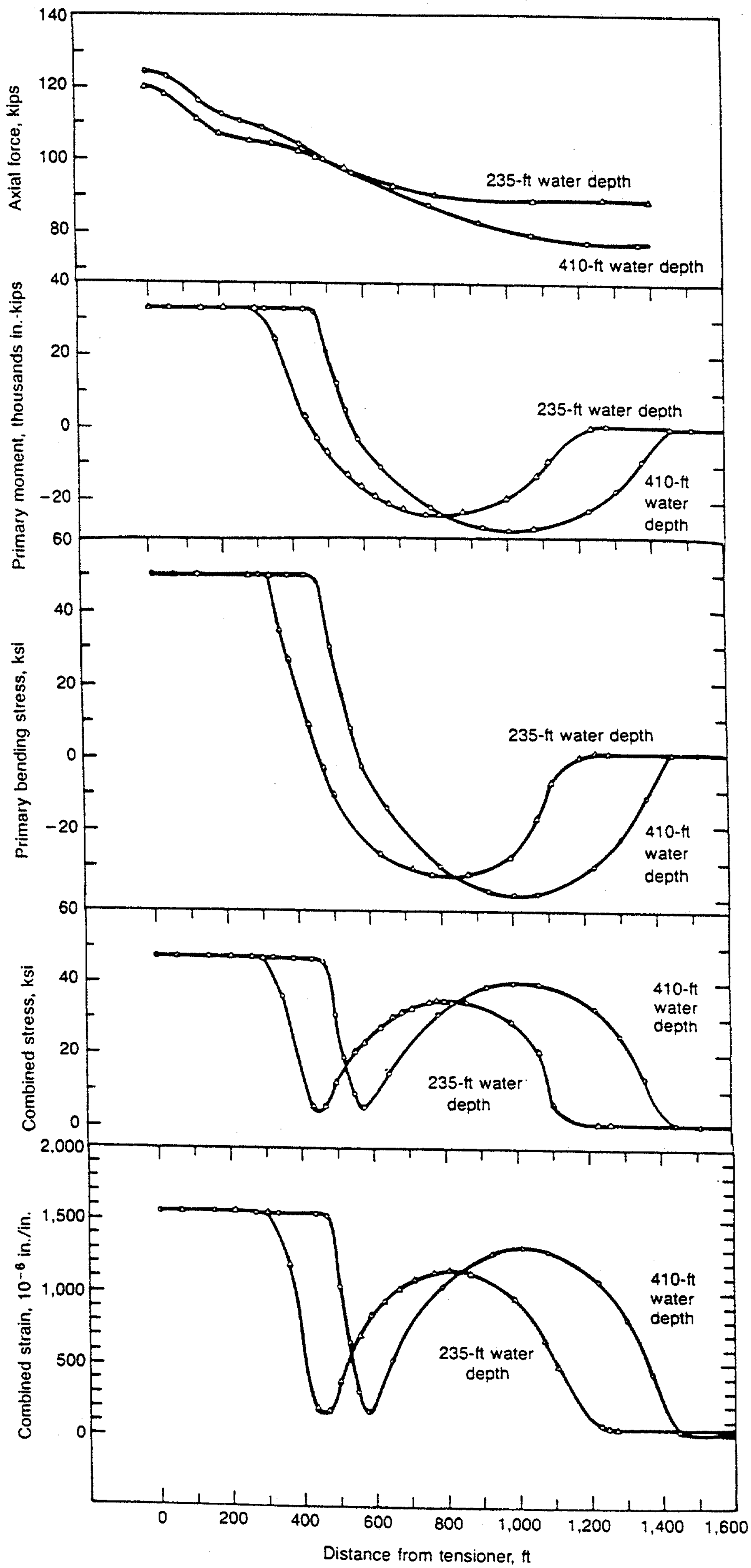


Pipeline coordinates

REF. B2

RESULTS FROM ANALYSES

CHART 2-2



REF. B2

CHART 3-1

OIL SPILL INCIDENTS OF 238 OR MORE BARRELS

OCS-GULF OF MEXICO

Calendar Year	Incidents	Oil Spilled	Number of Structures	Annual OCS Oil Production
1964	5	14,928 barrels	1,100	115 million barrels
1965	2	2,188 barrels	1,200	136 million barrels
1966	0	None	1,325	175 million barrels
1967	1	160,639 barrels	1,450	206 million barrels
1968	1	6,000 barrels	1,575	250 million barrels
1969	4*	10,624 barrels*	1,675	285 million barrels
1970	3	83,895 barrels	1,800	312 million barrels
1971	1	450 barrels	1,891	359 million barrels
1972	0	None	1,935	356 million barrels
1973	4	22,175 barrels	2,001	342 million barrels
1974	2	22,046 barrels	2,054	316 million barrels
1975	0	None	2,079	288 million barrels
1976	2	4,300 barrels	2,096	281 million barrels
1977	2	550 barrels	2,248	250 million barrels
1978	0	None	2,327	255 million barrels
1979	1	1,500 barrels	2,420	246 million barrels
1980	1	1,456 barrels	2,554	232 million barrels
1981	1	5,100 barrels	2,744	228 million barrels**
Total	30	335,851 barrels	2,744	4,632 million barrels

*Revised 3/82 - Previous value, for 1969 30,024 barrels, included two spills which were not in OCS Gulf of Mexico.

**Preliminary value

SOURCE: MMS, NOLA

MAJOR ACCIDENTS ON THE U.S. OUTER CONTINENTAL SHELF
(1953 - 1972)

RESULT	CAUSE					
	Drilling	Production	Pipeline	Collision	Weather	Total
Accident Affecting:						
Oil	0	3	4	1	3	11
Oil and Gas	2	7	0	0	0	9
Gas	17	2	0	0	0	19
Other	0	3	0	1	0	4
Total	19	15	4	2	3	43
Oil Spills of Above: (a)			(b)			
Number	2	10	4	1	3	20
Volume- (Thou. Barrels)	18.5-780	84-135.4	175	2.6	9.2-9.7	290-1,100
Tragedies:						
Deaths	23	33	0	0	0	56
Injuries	7-8	91-100	0	0	0	98-108
Fires	7	12	0	1	0	20
Major Damage to Platform Rig	4	9	0	2	0	15
Duration	2 hrs.- 5.5 mos.	10 min.- 4.5 mos.	1-13 days	1 day	1-3 days	10 min.- 5.5 mos.

(a) spills of about 1,000 barrels or more in OCS waters

(b) Four pipeline spills are:

October 15, 1967	West Delta Blk. 73	160,639 bbls.
March 12, 1968	So. Timbalier Blk. 131	6,000 bbls.
February 11, 1969	Main Pass Blk. 299	7,532 bbls.
December 16, 1969	Santa Barbara Channel	900 bbls.

REF. F5,U2

CHART 3-3

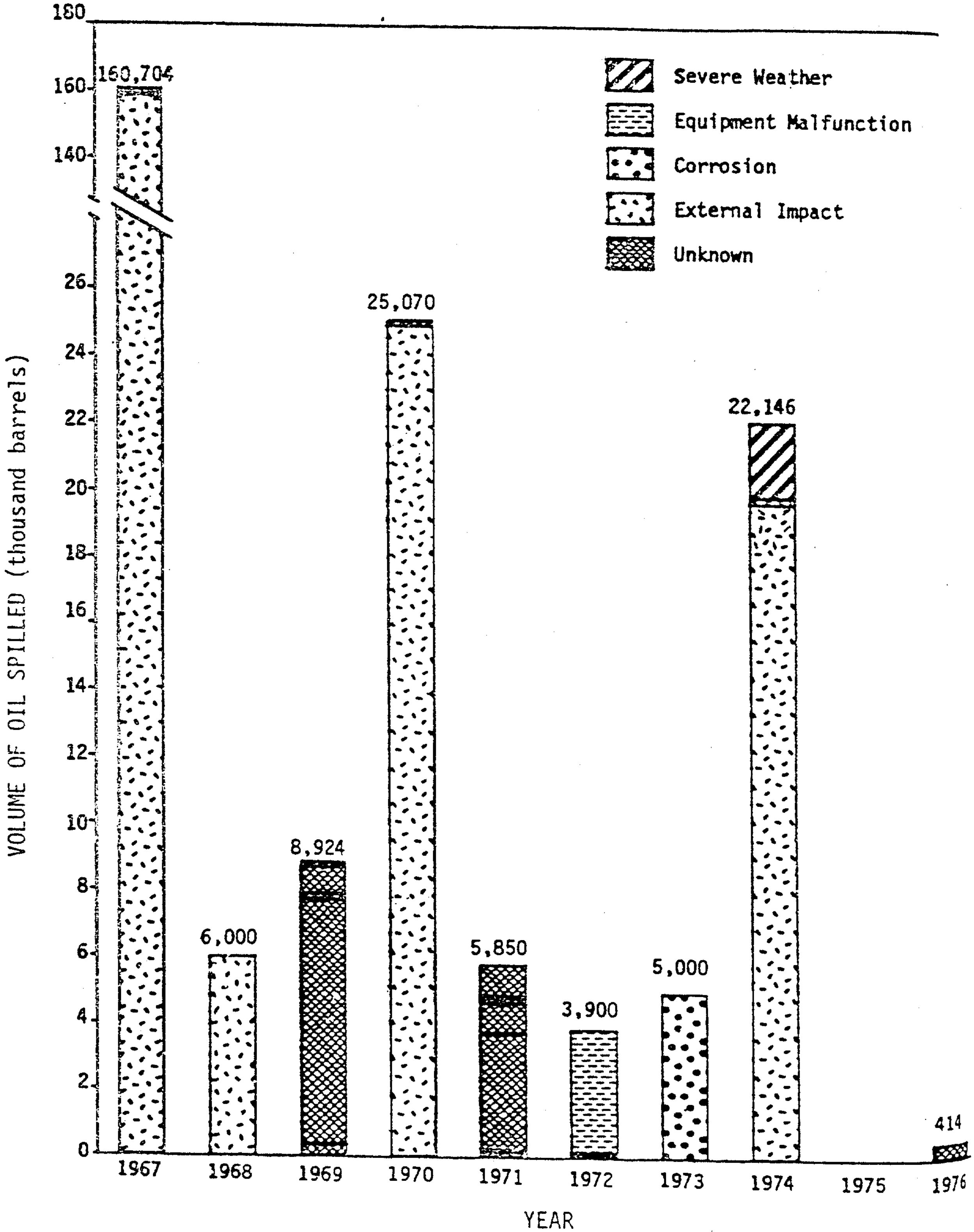
ANALYSIS OF DATA BASE OF OIL SPILLS FROM U.S. OFFSHORE PIPELINES[a]

CAUSE OF LEAK OR BREAK	VOLUME SPILLED (bbls.)										10-YEAR CUMULATIVE DATA			
											VOLUME OF SPILLS		NUMBER OF SPILLS	
	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Volume	Percentage	Number	Percentage
- External Impact (i.e., anchor dragging dredging, fishing boards)	160,639	6,000	-	25,000	80	-	-	19,933	-	-	211,652	88.9%	6	27.4%
- Corrosion	-	-	-	-	-	-	5,000	-	-	-	5,000	2.1%	1	4.5%
- Equipment Malfunction	-	-	100	-	-	3,800	-	-	-	-	3,900	1.7%	2	9.1%
- Severe Weather	-	-	-	-	-	-	-	2,213	-	-	2,213	0.9%	1	4.5%
- Unknown	65	-	8,824	70	5,770	100	-	-	-	414	15,243	6.4%	12	54.5%
TOTAL	160,704	6,000	8,924	25,070	5,850	3,900	5,000	22,146	0	414	238,008	100.0%	22	100.0%

(a) Spills of 50 barrels or more on OCS and Coastal Waters.

REF. F5

MAJOR U.S. OFFSHORE OIL SPILLS FROM PIPELINES



REF. F5

Causes of oil spills of 1-50 barrels, 1971-75, Gulf of Mexico OCS

Cause	Number of Spills	Total volume (bbl)	Volume (bbl) per spill Average	Maxi-mum	Mini-mum
Pipeline & Pump Failure:					
Pipeline leaked	63	303.5	4.82	35	1.5
Pipeline ruptured	20	161	8.05	32	2
Discharge or transfer line ruptured or coupling failed	54	237	4.39	27	1
Pipeline pump failed	42	211	5.02	20	1
Pig trap leaked	12	35	2.92	10	1
High-low pressure sensor failed	3	18	6.00	8	4
Fuel line leaked	2	3	1.50	2	1
Pump capacity exceeded	1	2	2.00	2	2
Miscellaenous	39	152	3.90	12	1
TOTAL	236	1,122.5	4.76	35	1
Production Platform Equipment Malfunction or Misuse	536	2,286	4.26	50	1
Drilling & Workover Mishaps	20	64.5	3.23	10	1
Miscellaneous Equipment Failures & Employee Errors	84	440	5.24	36	1
TOTAL	876	3,913	4.47	50	1

REF. D3, F5

CHART 3-6

OCS GULF OF MEXICO OIL SPILLS, 50 BARRELS OR LESS

	1971	1972	1973	1974	1975
Total volume of spills (bbls)	104	68	87	117	89
Total number of spills	12	12	17	17	25
Average volume per spill (bbls)	8.67	5.67	5.12	6.88	3.56
% Change in Average Vol. from Preceding Year	--	-34.6%	-9.7%	+21.3%	-48.3%

Cause	No. of Spills	Total Volume (bbls)
Pipeline leaks	63	303.5
Pipeline ruptures	20	161
	83	464.5

Pipeline spills as % of total # of spills	=	9.5%
Pipeline spill Vol. as % of total spill Vol.	=	11.9%
Quantity per pipeline spill, average per spill	=	5.6 bbls.
Quantity spilled from pipelines, average per year	=	93 bbls.

REF. F5

CAUSES OF OIL SPILLS OF MORE THAN 50 BARRELS, 1971-75

GULF OF MEXICO OCS

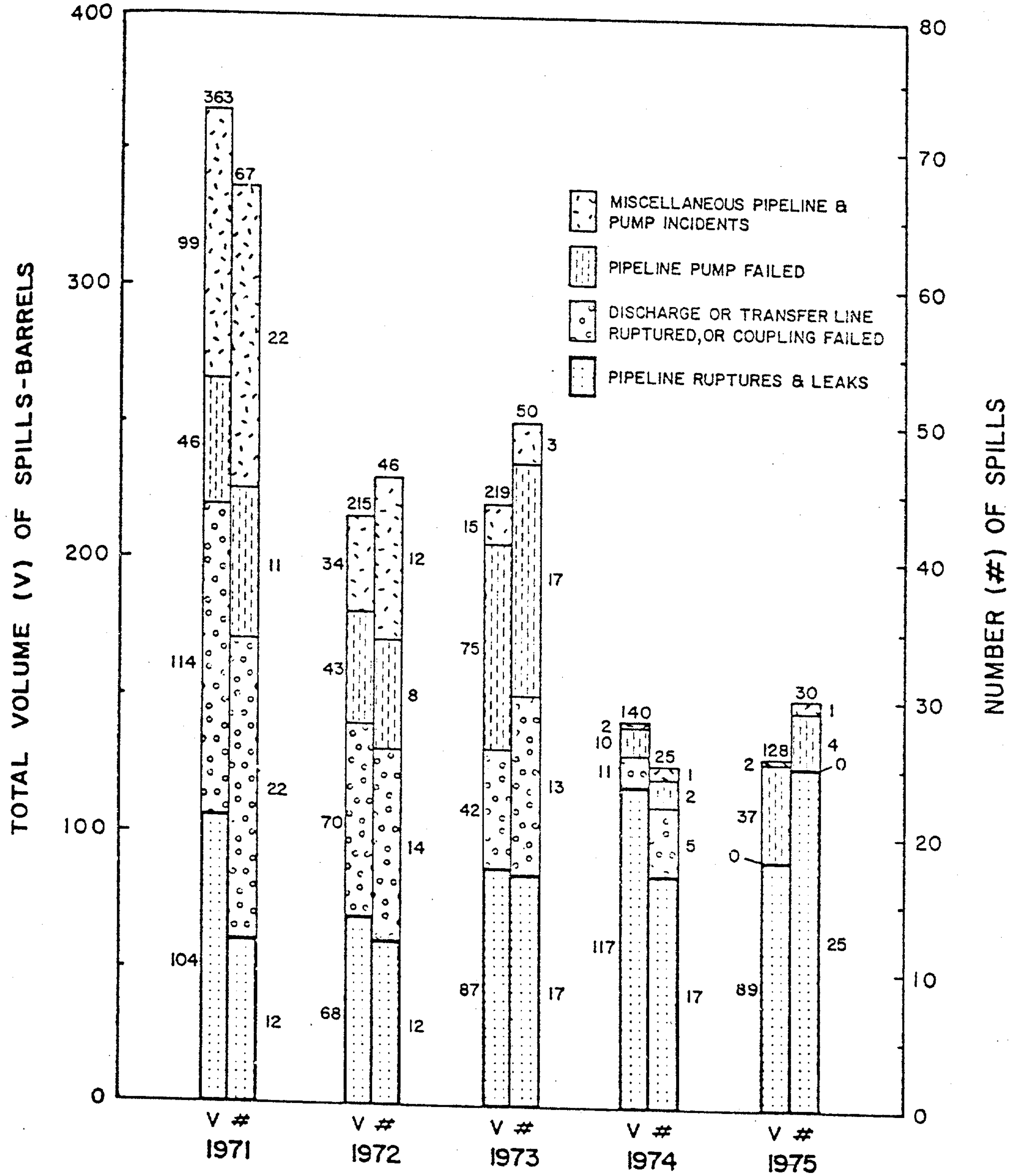
Cause	Number of Spills	Total Volume (bbl)	Volume (bbl) per spill Maximum	Minimum
Pipeline leaks and breaks	7*	27,396	19,833	70
Production-platform equipment malfunction or misuse	6	10,925	9,935	75
Drilling and workover mishaps	0	0	0	0
Barge spill (leaks; or oil transfer)	2	7,100	7,000	100
Workboat spillage during unloading of diesel fuel; or collision with platform	3	506	240	100
Other causes	2	320	200	120
Total	20	46,247	-	-

*Spills in Federal waters of Gulf of Mexico OCS:

1.	Nov. 14, 1971	West Delta Blk. 29	70 bbls.
2.	Dec. 17, 1971	Eugene Is. Blk. 238	80 bbls.
3.	June 26, 1972	West Delta Blk. 79	100 bbls.
4.	May 12, 1973	West Delta Blk. 73	5,000 bbls.
5.	April 17, 1974	Eugene Is. Blk. 317	19,833 bbls.
6.	May 21, 1974	Eugene Is. Blk. 331	100 bbls.
7.	Sept. 9, 1974	Main Pass Blk. 73	2,213 bbls.
			27,396 bbls.

REF. D3, F5

GULF OF MEXICO OCS PIPELINE AND PUMP SPILLS, 1-50 BARRELS



REF. D3,F5

CHART 3-9

ANNUAL STATISTICS OF SPILLS FROM LIQUID PIPELINE ACCIDENTS (U.S. ONSHORE & OFFSHORE)

CAUSE	NUMBER OF SPILLS 1968	1969	1970	1971	1972	1973	1974	1975	1976
EXTERNAL CORROSION	216	155	149	102	75	72	52	57	41
INTERNAL CORROSION	16	17	30	22	25	14	15	16	10
OPERATIONAL CAUSES (1)	14	15	20	22	24	16	28	22	20
EQUIPMENT MALFUNCTION OR FAILURE (2)	18	18	6	10	10	16	10	27	15
SEVERE WEATHER (3)	4	5	1	5	14	14	9	2	6
CONSTRUCTION DEFECTS (4) OR MATERIAL FAILURE (5)	80	58	46	56	62	56	29	26	20
EXTERNAL IMPACT (6)	106	102	75	73	86	74	90	81	78
MISCELLANEOUS & UNKNOWN	45	33	20	18	13	11	23	29	19
TOTAL	499	403	347	308	309	273	256	260	209

CAUSE	VOLUME OF SPILLS (bbls) 1968	1969	1970	1971	1972	1973	1974	1975	1976
EXTERNAL CORROSION	69,904	70,878	45,232	29,925	40,475	32,637	21,399	37,073	31,954
INTERNAL CORROSION	7,863	5,725	15,616	12,445	38,988	11,455	3,901	2,853	3,249
OPERATIONAL CAUSES (1)	13,237	22,687	32,541	22,830	46,185	63,144	20,957	26,619	40,155
EQUIPMENT MALFUNCTION OR FAILURE (2)	8,146	18,153	16,273	16,266	6,293	11,891	13,474	20,981	5,866
SEVERE WEATHER (3)	6,919	5,535	2,500	4,860	31,799	22,975	6,299	11,356	4,365
CONSTRUCTION DEFECTS (4) OR MATERIAL FAILURE (5)	95,758	99,899	45,265	65,646	59,948	169,510	53,485	94,440	51,847
EXTERNAL IMPACT (6)	114,587	96,409	81,531	74,907	123,896	63,600	120,347	116,273	102,587
MISCELLANEOUS & UNKNOWN	76,167	24,325	282,891	18,178	13,070	4,153	53,781	9,828	15,014
TOTAL	392,581	343,691	521,849	245,057	360,654	379,365	293,643	319,423	255,037

CAUSE	SPILLS BY CAUSE AS PERCENT OF TOTAL NUMBER OF SPILLS (7) 1968	1969	1970	1971	1972	1973	1974	1975	1976
EXTERNAL CORROSION	43.3	38.5	42.9	33.1	24.3	26.4	20.3	21.9	19.6
INTERNAL CORROSION	3.2	4.2	8.6	7.1	8.1	5.1	5.9	6.2	4.8
OPERATIONAL CAUSES (1)	2.8	3.7	5.8	7.1	7.8	5.9	10.9	8.5	9.6
EQUIPMENT MALFUNCTION OR FAILURES (2)	3.6	4.5	1.7	3.2	3.2	5.9	3.9	10.4	7.2
SEVERE WEATHER (3)	0.8	1.2	0.3	1.6	4.5	5.1	3.5	0.8	2.9
CONSTRUCTION DEFECTS (4) OR MATERIAL FAILURE (5)	16.0	14.4	13.3	18.2	20.1	20.5	11.3	10.0	9.6
EXTERNAL IMPACT (6)	21.2	25.3	21.6	23.7	27.8	27.1	35.2	31.2	37.3
MISCELLANEOUS & UNKNOWN	9.0	8.2	5.8	5.8	4.2	4.0	9.0	11.2	9.1
TOTAL	100%	100%	100%	100%	100%	100%	100%	100%	100%

CAUSE	SPILLS BY CAUSE AS PERCENT OF TOTAL VOLUME OF SPILLS (7) 1968	1969	1970	1971	1972	1973	1974	1975	1976
EXTERNAL CORROSION	17.8	20.6	8.7	12.2	11.2	8.6	7.3	11.6	12.5
INTERNAL CORROSION	2.0	1.7	3.0	5.1	10.8	3.0	1.3	0.9	1.3
OPERATIONAL CAUSES (1)	3.4	6.6	6.2	9.3	12.8	16.6	7.1	8.3	15.7
EQUIPMENT MALFUNCTION OR FAILURES (2)	2.1	5.3	3.1	6.6	1.7	3.1	4.6	6.6	2.3
SEVERE WEATHER (3)	1.8	1.6	0.5	2.0	8.8	6.1	2.1	3.6	1.7
CONSTRUCTION DEFECTS (4) OR MATERIAL FAILURE (5)	24.4	29.1	8.7	26.8	16.6	44.7	18.2	29.6	20.3
EXTERNAL IMPACT (6)	29.2	28.1	15.6	30.6	34.4	16.8	41.0	36.4	40.2
MISCELLANEOUS & UNKNOWN	19.4	7.1	54.2	7.4	3.6	1.1	18.3	3.1	5.9
TOTAL	100%	100%	100%	100%	100%	100%	100%	100%	100%

(1) Incorrect operation by carrier personnel, surge of electricity and surge of flow.
(2) Malfunction of control or relief equipment, malfunction of valve, pump failure, pump packing failure, and tank roof drain leaking.
(3) Heavy rains or floods, cold weather, lightning and landslides.
(4) Defective girth weld, failure of previously welded repairs, and defective weld.
(5) Defective pipe seam, failure in river crossing, ruptured or leaking gasket, threads stripped or broken, pipe failed due to buckling, ruptured or leaking seal, pipe coupling failure, defective pipe, stress crack and wrinkle bend split.
(6) Equipment rupturing line, rupture of previously damaged pipe, freight train derailment, vandalism, and explosives.
(7) Percent figures may not total 100% due to rounding off.

REF. F5

CHART 3-10

ANNUAL AVERAGE VOLUME PER SPILL, BY CAUSE, FROM LIQUID PIPELINE ACCIDENTS

(U.S. ONSHORE & OFFSHORE)

CAUSE	AVERAGE VOLUME PER SPILL (bbls) 1968	1969	1970	1971	1972	1973	1974	1975	1976
External Corrosion	324	457	304	293	540	453	412	650	779
Internal Corrosion	491	337	521	566	1,560	818	260	178	325
Operational Causes(1)	946	1,512	1,627	1,038	1,924	3,947	748	1,210	2,008
Equipment Malfunction or Failures(2)	453	1,009	2,712	1,627	629	743	1,347	777	391
Severe Weather(3)	1,730	1,107	2,500	972	2,271	1,641	700	5,678	728
Construction Defects(4) or Material Failure(5)	1,197	1,722	984	1,172	967	3,027	1,844	3,632	2,592
External Impact(6)	1,081	945	1,087	1,026	1,441	859	1,337	1,435	1,315
Miscellaneous & Unknown	1,693	737	14,145	1,010	1,005	378	2,338	339	790
Overall Average	787	853	1,504	796	1,167	1,390	1,147	1,229	1,220

(1) Incorrect operation by carrier personnel, surge of electricity and surge of flow.
(2) Malfunction of control or relief equipment, malfunction of valve, pump failure, pump packing failure, and tank roof drain leaking.
(3) Heavy rains or floods, cold weather, lightning and landslides.
(4) Defective girth weld, failure of previously welded repairs, and defective weld.
(5) Defective pipe seam, failure in river crossing, ruptured or leaking gasket, threads stripped or broken, pipe failed due to buckling, ruptured or leaking seal, pipe coupling failure, defective pipe, stress crack and wrinkle bend split.
(6) Equipment rupturing line, rupture of previously damaged pipe, freight train derailment, vandalism, and explosives.

REF. F5

CHART 3-11

ANNUAL STATISTICS OF FAILURES OF GAS PIPELINES (U.S. ONSHORE AND OFFSHORE), 1970-1976[1]

CAUSE	NUMBER OF FAILURES							FAILURES BY CAUSE AS PERCENT OF DISTRIBUTION, AND TRANSMISSION & GATHERING LINE FAILURES[2]						
	1970	1971	1972	1973	1974	1975	1976	1970	1971	1972	1973	1974	1975	1976
DISTRIBUTION LINES:														
Corrosion	102	120	121	133	108	94	118	15.1	13.7	13.7	14.9	10.6	9.6	11.4
Damage by Outside Forces	462	575	630	602	756	744	659	68.3	65.6	71.3	67.4	74.3	76.0	63.6
Construction Defect or Material Failure	53	121	90	92	94	78	115	7.8	13.8	10.2	10.3	9.2	8.0	11.1
Other Causes	59	61	43	66	59	63	144	8.7	7.0	4.9	7.4	5.8	6.4	13.9
Subtotal	676	877	884	893	1017	979	1036	100%	100%	100%	100%	100%	100%	100%
TRANSMISSION & GATHERING LINES:														
Corrosion	51	55	74	63	78	44	115	14.9	13.4	18.1	13.4	17.0	11.2	21.2
Damage by Outside Forces	181	213	219	272	274	237	219	52.8	52.0	53.5	57.7	59.6	60.2	40.3
Construction Defect or Material Failure	88	105	80	111	81	88	180	25.7	25.6	19.6	23.6	17.6	22.3	33.1
Other Causes	23	37	36	25	27	25	29	6.7	9.0	8.8	5.3	5.9	6.3	5.3
Subtotal	343	410	409	471	460	394	543	100%	100%	100%	100%	100%	100%	100%
GAS INDUSTRY TOTAL	1019	1287	1293	1364	1477	1373	1579							

(1) Data for 1968 was not collected and is not reported. 1969 data is incomplete.
(2) Percent figures may not total 100% due to rounding off.

REF. F5

PIPELINE CODE COMPARISONS WITH WEST EUROPE COUNTRIES

Gas Pipe Line Code Comparisons

Code	Safety Factor	Design on Min. or Nominal Wall Thickness	Allowable Excess Pressure	Main Line Valve Frequency	Special Remarks	Normal Temperature Range
ANSI B31.8—1968	1.4 to 2.5	Nominal. But may be corrected by design factor F.	Lesser of, 10% overpressure, or pressure to produce 75% of yield.	Every 5 to 20 miles depending on location.	Safety factor varied as function of building density.	
Institute of Petroleum (U.K.)	1.4 or 1.67	Minimum	10% overpressure	Every 10 miles in open country, and at special locations	Both codes specify reduction in safety factor as function of pressures and buildings proximity following principal of USSR National Gas Code (1960) but ANSI B31.8 and IGE procedures accepted as optional.	−13°F to 248°F
British Standard Code of Practice CP2010 Part 2 1970.	1.4 or 1.67	Minimum	10% surge	Every 10 miles in open country, and at special locations		−13°F to 250°F
Institution of Gas Engineers (U.K.)	1.40 in open country 2.2 close to inhabited building.	Minimum	None	Not greater than 10 miles in open country. Spacing reduced in built-up areas.	Use of 0.72 stress factor limited to population density of one per acre. 0.55 is more common 0.40 in urban areas. Pressures also limited by building proximity.	
Belgium	1.48 to 1.34	Nominal	10% overpressure	At branches and other appropriate locations		
International Gas Union Safety Code	1.40 to 2.5 but restriction on yield to ultimate ratio.	Nominal	None	30 km maximum except in desert regions.	Adopted by EEC committee on gas (1965). Based on ANSI B31.8 and USSR Codes which differ primarily on area classification method.	

Liquid Pipe Line Code Comparisons

Code	Safety Factor	Designed on Minimum or Nominal Wall	Allowable Excess Pressure	Main Line Valve Frequency	Special Remarks	Normal Temperature Range
ANSI B.31.4 1966	1.4	Nominal	10% surge	At river crossings and as dictated by the terrain.		−20°F to 250°F
Institute of Petroleum (U.K.)	1.4	Minimum	10% overpressure	To provide a maximum drainable length of 10 miles and at crossings.		13°F to 248°F
RFF & DIN 2413 (GERMANY)	1.7 average	Minimum	None		Dependent on material, fatigue and temperature conditions SF may increase to 2.5.	
AUSTRIAN ASSOCIATION OF THE MINERAL OIL INDUSTRY	1.4	Minimum	10% overpressure	According to terrain to limit the amount of potential spillage.		−13°F to 248°F
Belgium	1.48 to 1.34	Nominal	10% overpressure	At all branches and as required.		−13°F to 248°F
French	1.22 to 2.28	Minimum	10% surge		Yield valves to which SF applies determined on different principles to ANSI.	up to 248°F
British Standard Code CP2010 Part 2 1970	1.4	Minimum	10% surge	To provide a maximum drainable length of 10 miles and at crossings.		−13°F to 250°F
E.E.C. Draft	Normal areas 1.35 to 1.6 Desert area 1.22	Minimum	10% surge	To limit drainable lengths as dictated by terrain but kept to minimum.	SF may be varied by the "Competent national authority".	−25°C (13°F) +120°C (248°F)

REF. P8

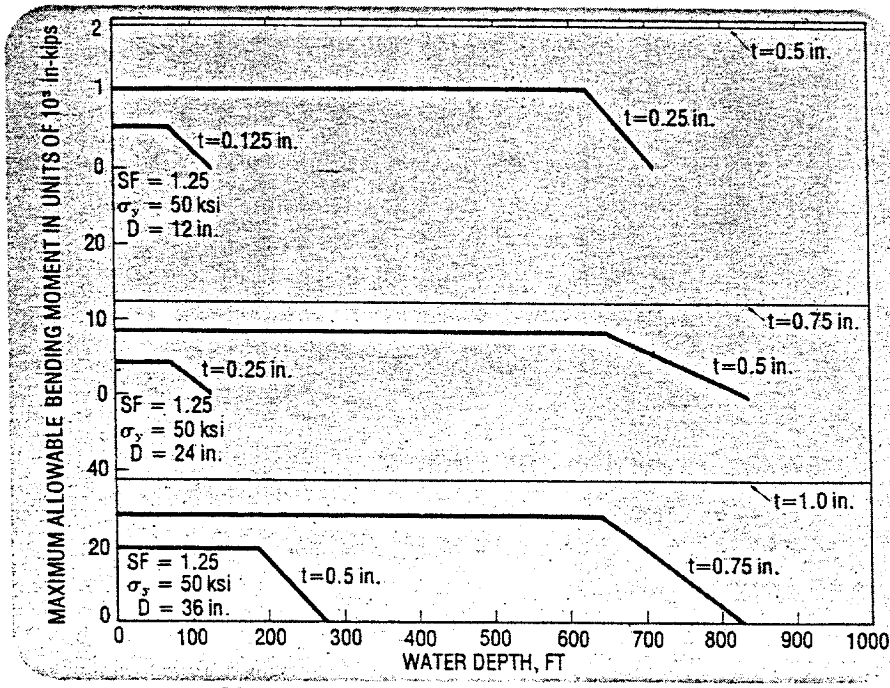
CHART 4-2

Offshore pipeline burial requirements

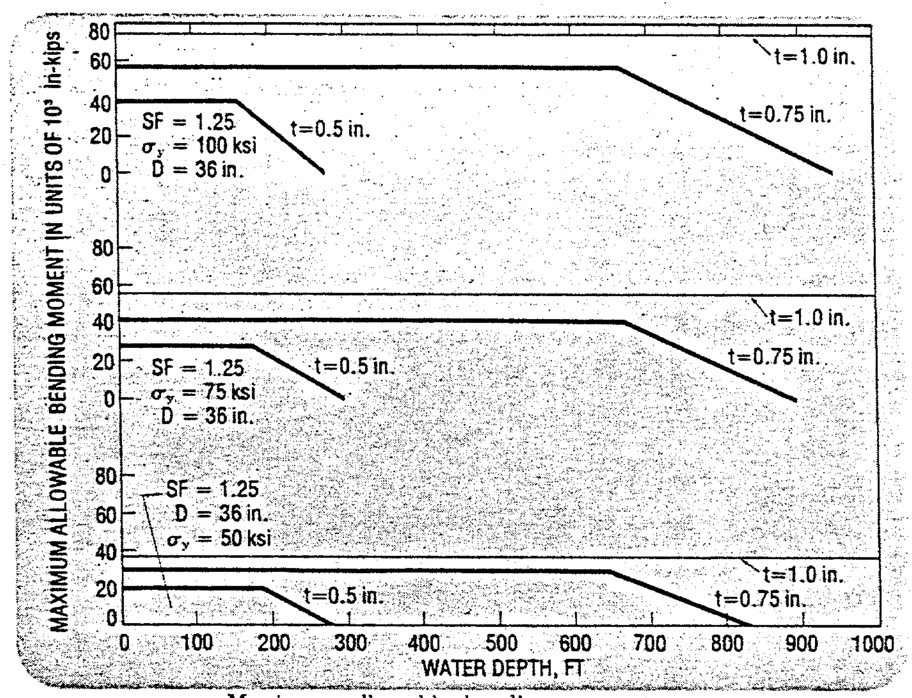
Country/Agency	Applicable code	Requirements
1. UNITED STATES		
• Department of Transportation (DOT)—Office Pipeline Safety Operations (OPSO)	49 CFR 192 49 CFR 195	Pipeline to be buried below natural bottom.
• Department of Interior (DOI)		
—U.S. Geological Survey (USGS)	OCS Order 9	No specific requirement.
—Bureau of Land Management (BLM)	43 CFR 2883	Pipeline must be buried to 3 ft. below the natural seabed out to a water depth of 200 ft.
2. UNITED KINGDOM		
• Department of Energy (DOE)	Petroleum Pipeline Safety Code 1974 Submarine Pipeline Act, 1975	General guidelines for pipe protection. "The Secretary of State may by regulation make such provisions as he considers appropriate for the purpose of securing the proper construction and preparation in safety operation of pipelines preventing damage to pipelines and securing the safety, health and welfare of persons engaged on pipeline works . . . "
3. NORWAY		
• Ministry of Petroleum and Energy	Norwegian Petroleum Directorate (NPD), Royal Decrees, 1976	"To the extent reasonable, pipelines shall be protected by burial or by other means to avoid mechanical damage caused by other activities along the route, including fishing and hunting, shipping, and exploration of submarine natural resources. Moreover, the pipelines shall be installed so as not to damage fishing gear."
• Industry Reccommended Practice	Det norske Veritas (DnV), 1976	"The pipeline is to be supported, anchored or buried in such a way that under the assumed conditions it will not move from its as-installed position, apart from movement corresponding to permissible deformation, thermal expansion, and limited amount of settlement after installation."
4. NETHERLANDS		
• Inspector General of Mines	Submarine Pipelines for Transport of Gas, 1976	Requirements for burial in shipping lanes or fishing areas to insure safety.
5. JAPAN		
• Ocean Development Safety Division	Standard for Safety Concerning oil and natural gas development, Part 2, Volume 3	General guidelines provided for safety and pipeline stability. However, past experiences has shown that severe burial requirements and possible backfill can be imposed for pipelines crossing areas of fishing activities.
6. AUSTRALIA		
• Standards Association of Australia	Draft-Australian Standard Rules for Submarine Pipelines, 1974	No specific requirement for burial. Section 5.7—Burying states: "The location of underwater obstructions intersecting the ditch route should be determined in advance of construction activities to prevent damage to such structures. A diver or television inspection shall be made of the ditch ahead of laying operations to insure that the specifications are met."

REF. M8

ALLOWABLE BENDING MOMENT

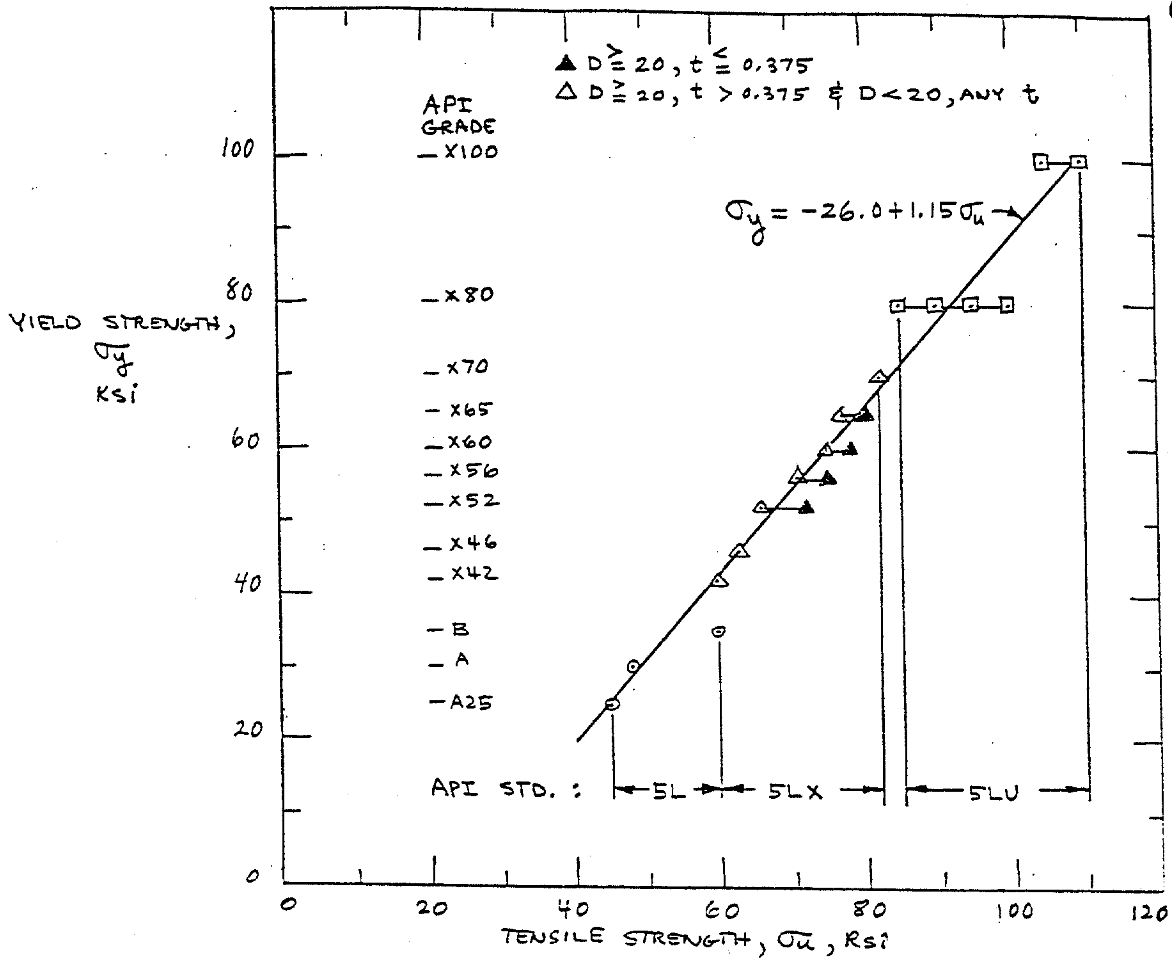


Maximum allowable bending moment vs water depth for various pipeline diameters.

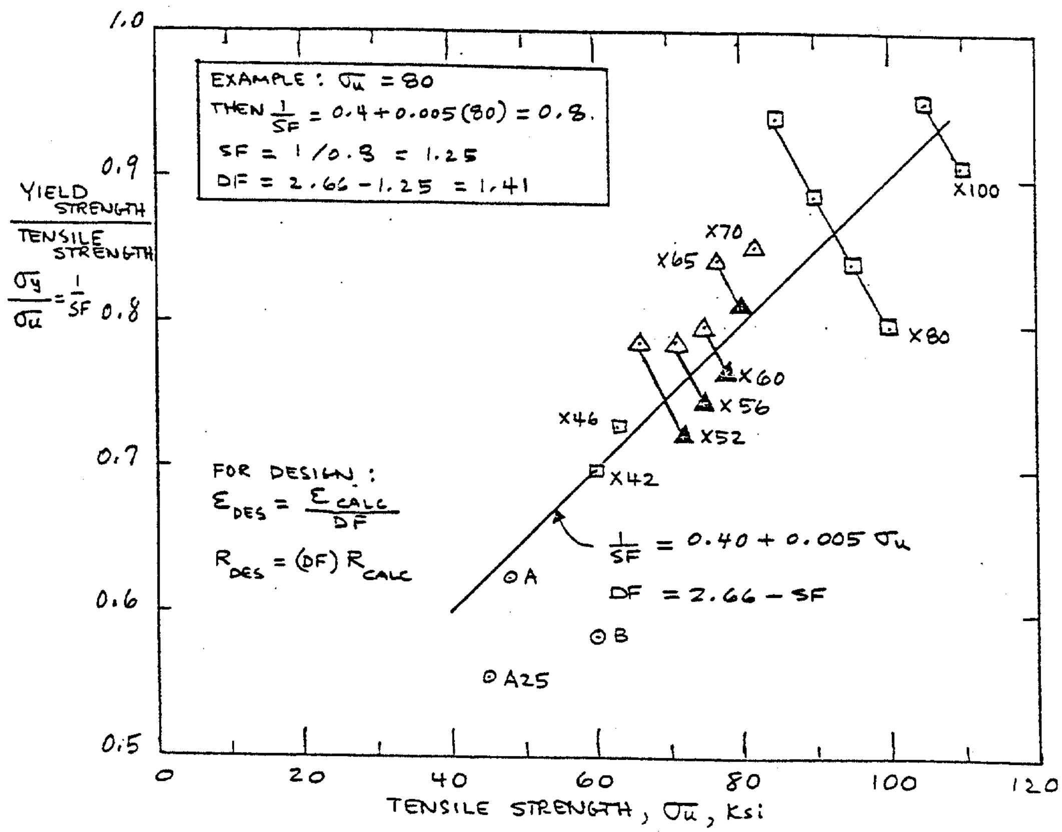


Maximum allowable bending moment vs water depth for various yield stress values.

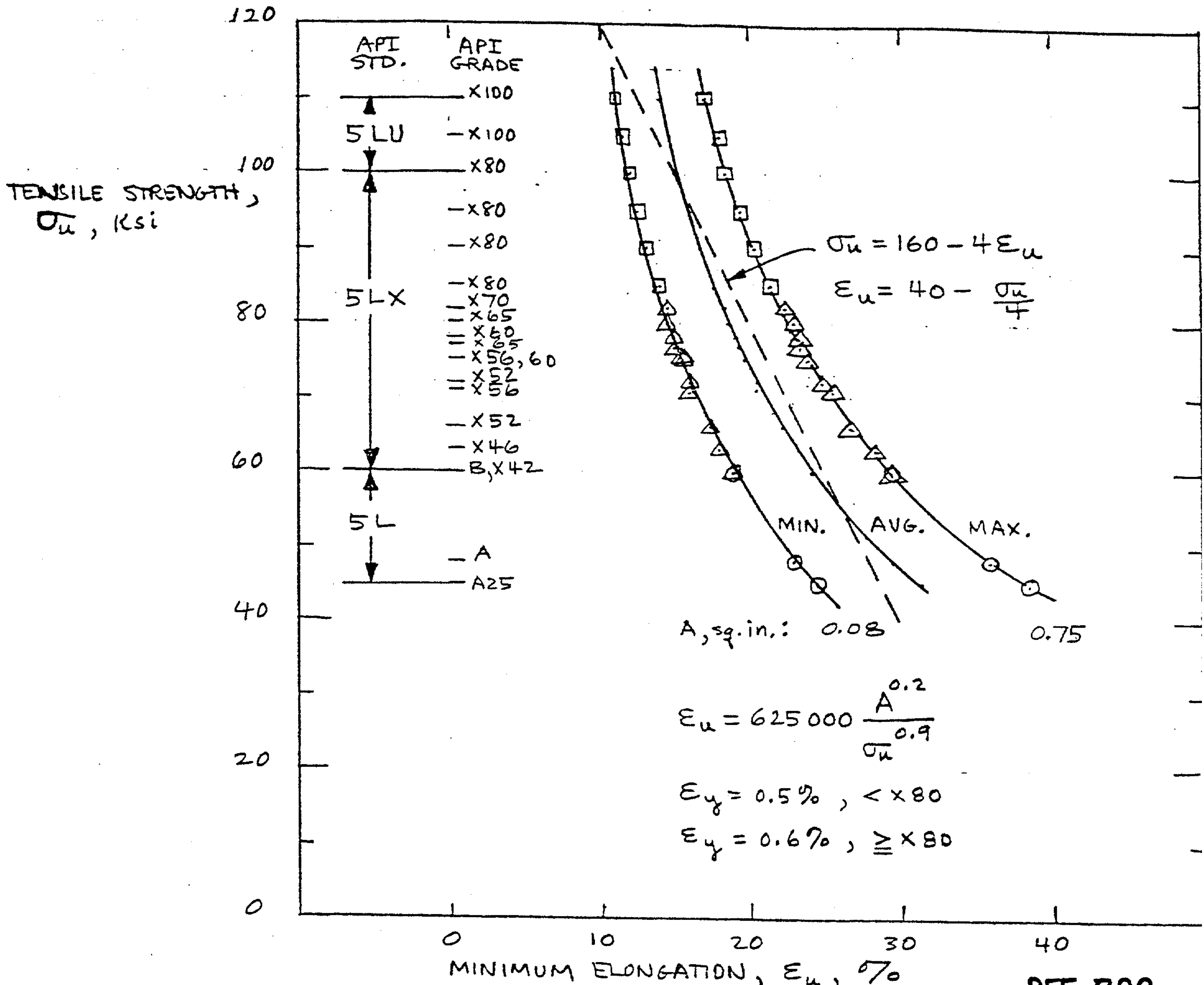
REF. B4



TENSILE STRENGTH OF API GRADE PIPE



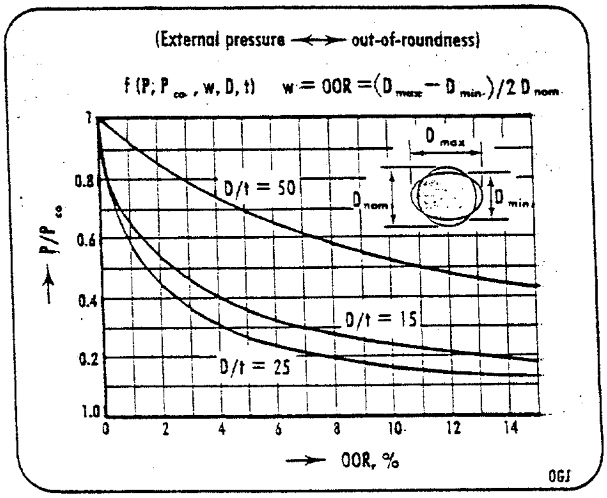
STRENGTH FACTOR FOR API GRADE PIPELINES



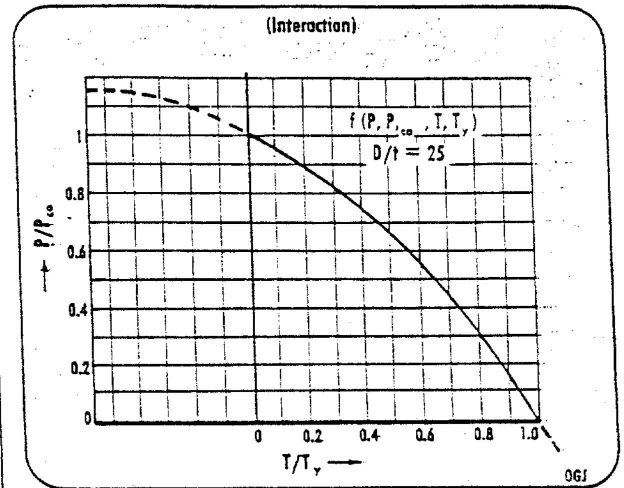
REF. B22

VARIATION OF MINIMUM ELONGATION WITH TENSILE STRENGTH

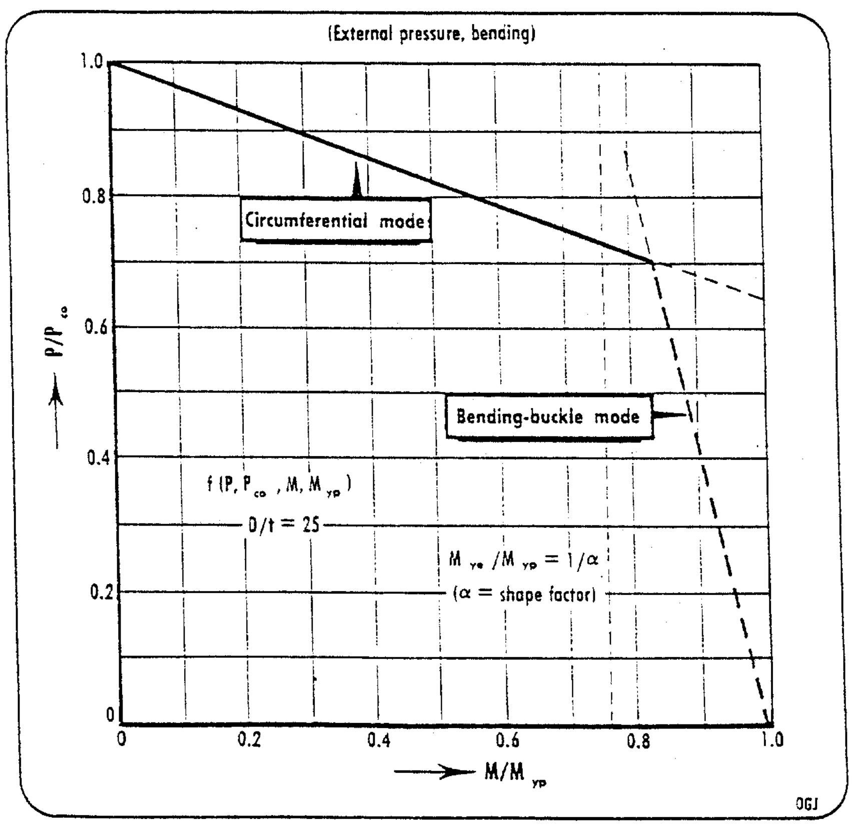
Interaction for grade B



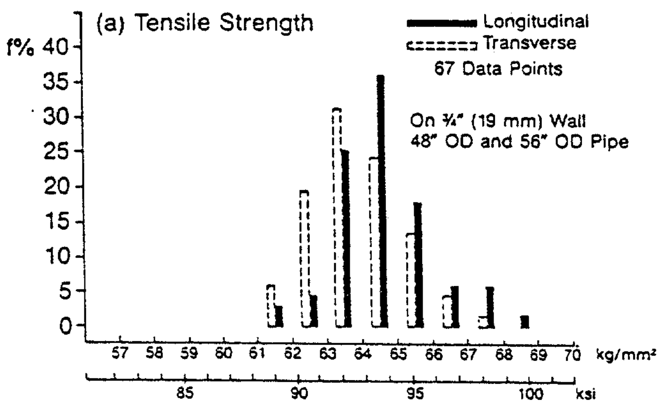
External pressure, axial tension

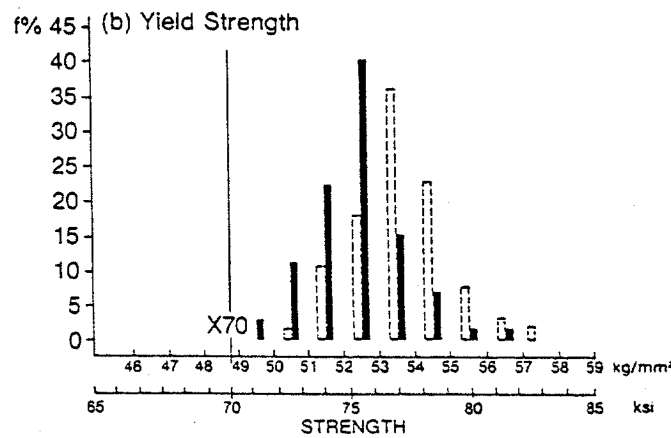


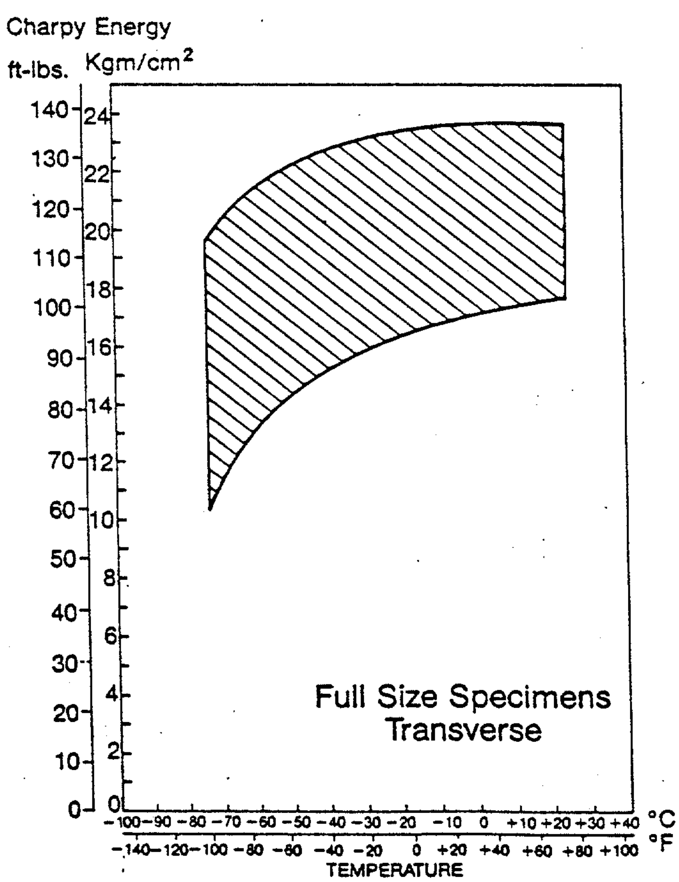
Bending-buckle type of failure

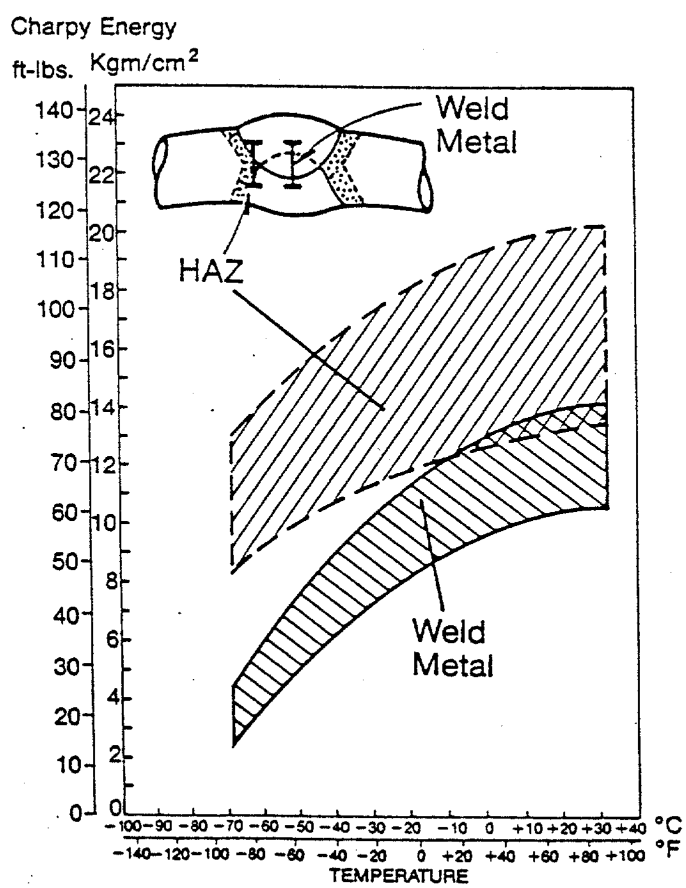


PROPERTIES OF FERRITIC X70 PIPE









PROPERTIES OF SAW X70 PIPE

Specification: API 5LXX70
Dimensions: Plate—19.5 mm (0.77 in.) x 436 cm (171.5 in.)
Pipe—1.42 cm (56 in.) OD x 19.5 mm (0.77 in.) WT
Design Temperature: − 60° C (− 76° F)

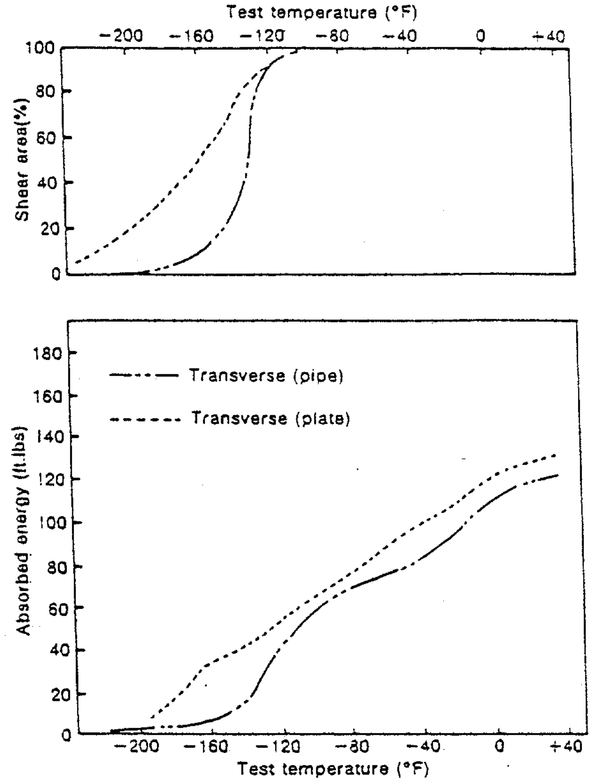
Typical chemical composition

	C	Si	Mn	P	S	Nb	CE*	Remarks
Ladle analysis (%)...	0.10	0.25	1.53	0.014	0.006	0.049	0.38	Other microalloy elements are also added.
Check analysis (%)...	0.10	0.26	1.54	0.013	0.005	0.051	0.38	

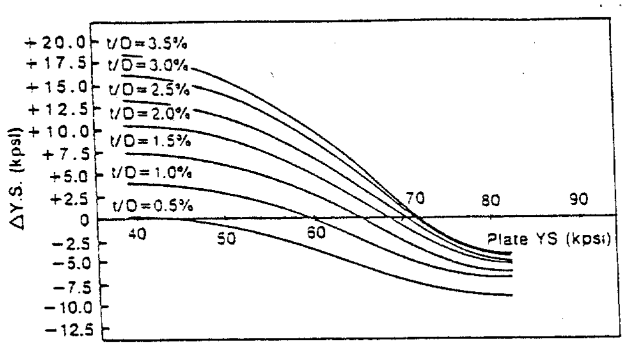
* CE = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15

Tensile test results:

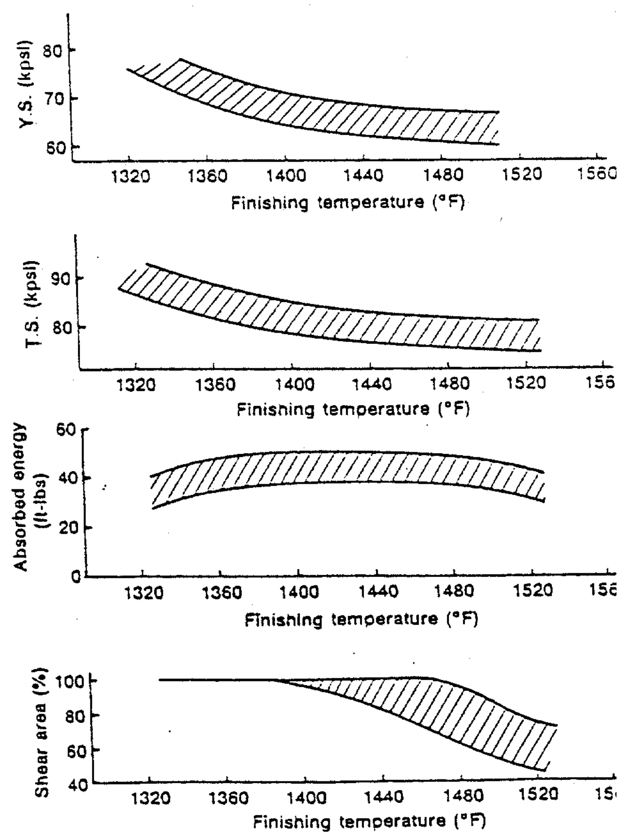
	YS ksi (kg/mm²)	TS ksi (kg/mm²)	YR (%)
Plate........................	74.4 (52.5)	90.2 (63.4)	83
Pipe.........................	78.2 (55.0)	93.9 (66.0)	83
X70 Spec.....................	70.0 (49.2) min.	82.0 (57.6) min.	90 max.

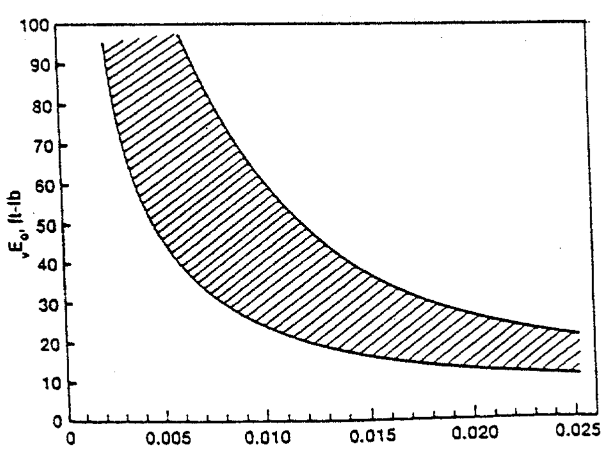


Charpy V-notch transition curves.



Difference in yield stress between pipe and plate plotted against yield stress of plate as function of t/D.





Effect of desulfurization on transverse Charpy

Relation between finishing temperature and mec ical properties.

REF. U1

CHART 6-3

DESIGN PROPERTIES OF API 5L, 5LX PIPE, 2-20 INCH DIAMETERS

NOMINAL PIPE SIZE and OUTSIDE DIAMETER inches	API SPECIFICATION NUMBER	WALL THICKNESS inches t	INSIDE DIAMETER inches d	FIFTH POWER of ID * in.^{5} d^5	AREAS and WEIGHTS: SURFACE AREA OUTSIDE sq ft per ft A_o	SURFACE AREA INSIDE sq ft per ft A_i	Cross-Sectional METAL AREA sq in. A	Cross-Sectional FLOW AREA sq in. A_f	WEIGHT of PIPE lb per ft w	WEIGHT of WATER lb per ft w_w	RADIUS of GYRATION inches r_g	MOMENT of INERTIA in.^{4} I	SECTION MODULUS in.^{3} Z
2 D = 2.375	5L	.083	2.209	52.60	.622	.578	.598	3.83	2.03	1.66	.81	.393	.33
3 D = 3.500	5L	.156	3.188	328.5	.916	.835	1.639	7.98	5.57	3.46	1.18	2.30	1.31
	5L	.250	3.000	243	.916	.785	2.553	7.07	8.68	3.06	1.15	3.39	1.94
	5L	.281	2.938	218.9	.916	.769	2.842	6.78	9.66	2.94	1.14	3.71	2.12
3½ D = 4,000	5L	.125	3.750	741.6	1.047	.982	1.521	11.05	5.17	4.78	1.37	2.86	1.43
	5L	.156	3.688	682.3	1.047	.966	1.884	10.68	6.41	4.63	1.36	3.49	1.74
	5L	.250	3.50	525.2	1.047	.916	2.945	9.62	10.01	4.17	1.33	5.20	2.60
4 D = 4.500	5L	.125	4.250	1387	1.178	1.113	1.931	13.97	6.57	6.05	1.54	4.59	2.04
	5L	.156	4.188	1288	1.178	1.096	2.129	13.78	7.24	5.97	1.54	5.03	2.24
	5L	.172	4.156	1240	1.178	1.088	2.339	13.57	7.95	5.87	1.53	5.49	2.44
	5L	.219	4.062	1106	1.178	1.063	2.950	12.96	10.01	5.61	1.52	6.77	3.01
5 D = 5.563	5L	.083	5.397	4579	1.456	1.413	1.420	22.88	4.83	9.91	1.94	5.33	1.92
	5L	.156	5.251	3992	1.456	1.375	2.641	21.66	8.98	9.38	1.91	9.66	3.47
	5L	.188	5.187	3755	1.456	1.358	3.166	20.13	10.76	9.15	1.90	11.45	4.12
	5L	.219	5.125	3536	1.456	1.342	3.666	20.63	12.46	8.93	1.89	13.11	4.72
	5L	.281	5.001	3128	1.456	1.309	4.654	19.64	15.82	8.51	1.87	16.28	5.85
	5L	.312	4.939	2939	1.456	1.293	4.714	19.16	16.03	8.30	1.86	17.77	6.39
	5L	.344	4.875	2753	1.456	1.276	5.631	18.67	19.15	8.08	1.85	19.26	6.92
6 D = 6.625	5L	.083	6.459	11.20T	1.734	1.691	1.706	32.77	5.80	14.19	2.31	9.13	2.76
	5L	.125	6.375	10.50T	1.734	1.669	2.553	31.92	8.68	13.82	2.30	13.49	4.07
	5L	.141	6.343	11.30T	1.734	1.661	2.872	31.60	9.77	13.68	2.29	15.11	4.56
	5L	.172	6.281	9.78T	1.734	1.644	3.487	30.99	11.86	13.42	2.28	18.17	5.49
	5L	.203	6.219	9.30T	1.734	1.628	4.096	30.38	13.93	13.15	2.27	21.14	6.38
	5L	.312	6.001	7.78T	1.734	1.571	6.188	28.28	21.04	12.25	2.24	30.91	9.33
	5L	.344	5.937	7.38T	1.734	1.554	6.788	27.68	23.08	11.99	2.22	33.58	10.13
	5L	.625	5.375	4.49T	1.734	1.407	11.781	22.69	40.06	9.83	2.13	53.60	16.18
8 D = 8.625	5L	.312	8.001	32.8T	2.258	2.095	8.149	50.28	27.71	21.77	2.94	70.50	16.35
	5L	.438	7.749	27.9T	2.258	2.029	11.266	47.16	38.30	20.42	2.90	94.68	21.96
	5L	.562	7.501	23.7T	2.258	1.964	14.236	44.19	48.40	19.14	2.86	116.3	26.96
10 D = 10.750	5L	.344	10.062	103.0T	2.81	2.63	11.246	79.52	38.24	34.43	3.68	152.43	28.36
	5L	.438	9.874	93.9T	2.81	2.59	14.190	76.57	48.25	33.16	3.65	189.0	35.16
	5L	.562	9.626	82.6T	2.81	2.52	17.988	72.78	61.16	31.51	3.61	234.2	43.56
	5L	.625	9.50	77.4T	2.81	2.48	19.881	70.88	67.60	30.69	3.59	255.8	47.59
	5L	.812	9.126	63.3T	2.81	2.39	25.352	65.41	86.20	28.32	3.53	315.1	58.63
12 D = 12.750	5L	.188	12.374	290T	3.34	3.24	7.420	120.36	25.22	52.07	4.44	146.4	22.97
	5L	.312	12.126	262T	3.34	3.17	12.192	115.49	41.45	50.00	4.40	236.0	37.01
	5L	.750	11.250	180T	3.34	2.95	28.275	99.40	96.14	43.04	4.25	511.1	80.17
14 D = 14.000	5L	.281	13.438	438T	3.67	3.52	12.111	141.8	41.18	61.41	4.85	285.1	40.73
	5L	.344	13.312	418T	3.67	3.49	14.758	139.9	50.18	60.27	4.83	344.3	49.19
	5L	.562	12.876	354T	3.67	3.37	23.726	130.2	80.67	56.38	4.76	537	76.66
	5L	.688	12.624	321T	3.67	3.30	28.773	125.2	97.83	54.20	4.71	639	91.32
	5L	.812	12.376	290T	3.67	3.24	33.643	120.3	114.39	52.09	4.67	734	104.90
16 D = 16.000	5LX	.203	15.594	922T	4.19	4.08	10.070	191.0	34.30	82.70	5.58	314	39.30
	5L	.562	14.876	729T	4.19	3.89	27.260	173.8	92.67	75.26	5.46	813	101.70
	5L	.625	14.750	698T	4.19	3.86	30.190	170.9	102.60	73.99	5.44	894	111.70
	5L	.812	14.376	614T	4.19	3.76	38.745	162.3	131.70	70.28	5.38	1121	140.10
18 D = 18.000	5LX	.219	17.562	1671T	4.71	4.60	12.230	242.2	41.60	104.9	6.29	484	53.70
	5L	.281	17.438	1612T	4.71	4.57	15.642	238.8	53.18	103.4	6.27	614	68.24
	5L	.344	17.312	1555T	4.71	4.53	19.081	235.4	64.88	101.9	6.24	744	82.67
	5LX	.406	17.188	1500T	4.71	4.50	22.410	232.0	76.30	100.5	6.22	869	96.60
	5LX	.469	17.062	1446T	4.71	4.47	25.830	229.0	87.80	99.0	6.20	993	110.40
20 D = 20.000	5L	.281	19.438	2775T	5.24	5.09	17.408	296.8	59.19	128.5	6.97	846	84.65
	5L	.344	19.312	2686T	5.24	5.06	21.243	292.9	72.23	126.8	6.95	1026	102.60
	5LX	.406	19.188	2601T	5.24	5.02	25.000	289.2	85.00	125.2	6.93	1200	120.00
	5LX	.469	19.062	2517T	5.24	4.99	28.780	285.4	97.80	123.6	6.91	1373	137.30
	5L	.688	18.624	2241T	5.24	4.88	41.742	272.4	141.92	117.9	6.83	1949	194.90
	5L	.750	18.500	2167T	5.24	4.84	45.357	268.8	154.20	116.4	6.81	2105	210.50

★ T = THOUSANDS, M = MILLIONS

REF. P8

DESIGN PROPERTIES OF API 5L, 5LX PIPE, 22-48 INCH DIAMETERS   CHART 6-4

NOMINAL PIPE SIZE and OUTSIDE DIAMETER inches	API SPECIFICATION NUMBER	WALL THICKNESS inches t	INSIDE DIAMETER inches d	FIFTH POWER of ID * in.^{5} d^5	AREAS and WEIGHTS: SURFACE AREA OUTSIDE sq ft per ft A_o	SURFACE AREA INSIDE sq ft per ft A_i	Cross-Sectional METAL AREA sq in. A	Cross-Sectional FLOW AREA sq in. A_f	WEIGHT of PIPE lb per ft w	WEIGHT of WATER lb per ft w_w	RADIUS of GYRATION inches r_g	MOMENT of INERTIA in.^{4} I	SECTION MODULUS in.^{3} Z
22 D = 22.000	5LX	.219	21.562	4661T	5.76	5.65	14.99	365.1	50.9	158.1	7.70	889	80.8
	5L	.281	21.438	4528T	5.76	5.61	19.17	360.9	65.1	156.3	7.68	1131	102.8
	5L	.344	21.312	4397T	5.76	5.58	23.40	356.7	79.6	154.5	7.66	1373	124.8
	5LX	.406	21.188	4270T	5.76	5.55	27.54	352.6	93.6	152.7	7.64	1606	146.0
	5L	.438	21.124	4206T	5.76	5.53	29.67	350.5	100.9	151.7	7.63	1725	156.9
	5LX	.469	21.062	4145T	5.76	5.51	31.72	348.4	107.9	150.9	7.61	1840	167.2
	5L	.562	20.876	3965T	5.76	5.47	37.85	342.3	128.7	148.2	7.58	2177	197.9
	5L	.688	20.624	3777T	5.76	5.40	46.06	334.1	156.6	144.7	7.54	2619	238.1
	5L	.812	20.376	3512T	5.76	5.33	54.05	326.1	183.8	141.2	7.50	3038	276.2
24 D = 24.000	5L	.281	23.438	7073T	6.28	6.14	20.94	431.5	71.2	186.8	8.39	1473	122.8
	5L	.344	23.312	6885T	6.28	6.10	25.57	426.8	86.9	184.8	8.37	1789	149.1
	5LX	.406	23.188	6704T	6.28	6.07	30.09	422.3	102.3	182.9	8.34	2095	174.6
	5LX	.469	23.062	6524T	6.28	6.04	34.67	417.7	117.9	180.9	8.32	2401	200.1
	5L	.812	22.376	5609T	6.28	5.86	59.15	393.2	201.1	170.3	8.20	3982	331.8
26 D = 26.000	5L	.250	25.500	10.80M	6.81	6.68	20.22	510.7	68.8	221.1	9.10	1677	128.9
	5L	.281	25.438	10.70M	6.81	6.66	22.70	508.2	77.2	220.1	9.09	1878	144.5
	5L	.344	25.312	10.40M	6.81	6.63	27.73	503.2	94.3	217.9	9.07	2282	175.6
	5LX	.406	25.188	10.13M	6.81	6.59	32.65	498.3	111.0	215.8	9.05	2674	205.7
	5LX	.469	25.062	9.89M	6.81	6.56	37.62	493.3	127.9	213.6	9.03	3067	235.9
	5L	.688	24.624	9.05M	6.81	6.45	54.71	476.22	186.0	206.2	8.95	4386	337
28 D = 28.000	5LX	.250	27.500	15.70M	7.33	7.20	21.80	594.0	74.1	257.2	9.81	2099	150
	5LX	.281	27.438	15.60M	7.33	7.18	24.47	591.3	83.2	256.0	9.80	2351	168
	5LX	.344	27.312	15.20M	7.33	7.15	29.89	585.9	101.6	253.7	9.78	2859	204
	5LX	.406	27.188	14.86M	7.33	7.12	35.20	580.6	119.7	251.4	9.76	3351	239
	5LX	.469	27.062	14.51M	7.33	7.09	40.56	575.2	137.9	249.1	9.74	3845	275
30 D = 30.000	5LX	.281	29.438	22.11M	7.85	7.71	26.24	680.6	89.2	294.7	10.51	2897	193
	5LX	.344	29.312	21.64M	7.85	7.67	32.05	674.8	109.0	292.2	10.49	3525	235
	5LX	.406	29.188	21.19M	7.85	7.64	37.75	669.1	128.3	289.7	10.46	4134	276
	5LX	.469	29.062	20.73M	7.85	7.61	43.51	663.3	147.9	287.2	10.44	4746	316
32 D = 32.000	5LX	.250	31.500	31.01M	8.38	8.25	24.94	779.3	84.8	337.4	11.23	3143	196
	5LX	.281	31.438	30.71M	8.38	8.23	28.00	776.2	95.2	336.1	11.21	3523	220
	5LX	.344	31.312	30.10M	8.38	8.19	34.21	770.0	116.3	333.4	11.19	4287	268
	5LX	.406	31.188	29.51M	8.38	8.17	40.30	764.0	137.0	330.8	11.17	5030	314
	5LX	.469	31.062	28.92M	8.38	8.13	46.46	757.8	158.0	328.1	11.15	5776	361
34 D = 34.000	5LX	.250	33.500	42.91M	8.90	8.77	26.51	881.4	90.1	381.6	11.93	3775	222
	5LX	.281	33.438	41.80M	8.90	8.75	29.77	878.2	101.2	380.3	11.92	4232	249
	5LX	.344	33.312	41.02M	8.90	8.72	36.37	871.5	123.7	377.4	11.90	5152	303
	5LX	.406	33.188	40.26M	8.90	8.69	42.85	865.1	145.7	374.6	11.88	6047	356
	5LX	.469	33.062	39.50M	8.90	8.66	49.41	858.5	168.0	371.7	11.86	6947	409
36 D = 36.000	5LX	.250	35.500	56.38M	9.42	9.29	28.08	989.8	95.5	428.6	12.64	4487	249
	5LX	.281	35.438	55.89M	9.42	9.28	31.53	986.3	107.2	427.1	12.63	5030	280
	5LX	.344	35.312	54.91M	9.42	9.25	38.53	979.3	131.0	424.0	12.61	6126	340
	5LX	.406	35.188	53.95M	9.42	9.21	45.40	972.5	154.4	421.1	12.59	7193	400
	5LX	.469	35.062	52.99M	9.42	9.18	52.35	965.5	178.0	418.1	12.56	8265	459
38 D = 38.000	5LX	.312	37.376	72.94M	9.95	9.79	36.94	1097	125.6	475.0	13.33	6561	345
	5LX	.344	37.312	72.32M	9.95	9.77	40.70	1093	138.4	475.3	13.31	7216	380
	5LX	.375	37.250	71.72M	9.95	9.75	44.33	1089	150.7	471.5	13.30	7846	413
	5LX	.406	37.188	71.12M	9.95	9.74	47.95	1086	163.0	470.2	13.29	8474	446
	5LX	.438	37.124	70.51M	9.95	9.72	51.69	1082	175.7	468.5	13.28	9119	480
	5LX	.469	37.062	69.93M	9.95	9.70	55.30	1078	188.0	466.8	13.27	9741	513
	5LX	.500	37.000	69.34M	9.95	9.69	58.91	1075	200.3	465.5	13.26	10359	545
	5LX	.562	36.876	68.19M	9.95	9.65	66.10	1068	224.7	462.4	13.24	11586	610
	5LX	.625	36.750	67.03M	9.95	9.62	73.39	1060	249.5	459.0	13.22	12821	675
40 D = 40.000	5LX	.344	39.312	93.89M	10.47	10.29	42.86	1213	145.7	525.2	14.02	8427	421
	5LX	.375	39.250	93.15M	10.47	10.28	46.68	1209	158.7	523.5	14.01	9165	458
	5LX	.406	39.188	92.42M	10.47	10.26	50.50	1206	171.7	522.2	14.00	9900	495
	5LX	.438	39.124	91.67M	10.47	10.24	54.44	1202	185.1	520.5	13.99	10655	533
	5LX	.469	39.062	90.94M	10.47	10.23	58.25	1198	198.0	518.7	13.98	11382	569
	5LX	.500	39.000	90.22M	10.47	10.21	62.05	1194	211.0	517.0	13.97	12106	605
	5LX	.562	38.876	88.80M	10.47	10.18	69.63	1187	236.7	514.0	13.95	13544	677
	5LX	.625	38.750	87.37M	10.47	10.15	77.31	1179	262.8	510.5	13.92	14991	750
42 D = 42.000	5LX	.406	41.188	118.54M	11.00	10.78	53.05	1332	180.4	576.8	14.71	11477	547
	5LX	.469	41.062	116.76M	11.00	10.73	61.19	1324	208.1	573.3	14.68	13198	629
48 D = 48.000	5LX	.406	47.188	233.97M	12.56	12.35	60.71	1749	206.4	757.3	16.83	17194	716
	5LX	.469	47.062	230.86M	12.56	12.32	70.03	1740	238.1	753.2	16.81	19784	824

* T = THOUSANDS, M = MILLIONS

RELATIONSHIP BETWEEN PIPE DIAMETER, LENGTH, AND VOLUME CONTAINED INSIDE

INSIDE DIAMETER (in.)	LENGTH REQUIRED TO HOLD 1000 BBL.		BARRELS PER MILE OF LINE	BARRELS PER KM. OF LINE
	Miles	Kilometers		
2.067	45.63	73.44	22	14
4.026	12.03	19.36	83	52
6.026	5.37	8.64	186	116
8.071	2.99	4.82	334	208
10.020	1.94	3.13	515	320
12.090	1.33	2.15	750	466
24.000	0.34	0.54	2,954	1,836
28.000	0.25	0.40	4,021	2,499
34.750	0.16	0.26	6,194	3,849
40.000	0.12	0.20	8,207	5,099
46.500	0.09	0.15	11,090	6,891

$$L(mi) = \frac{194.965}{D^2} \qquad V(/mi) = 5.129\ D^2$$

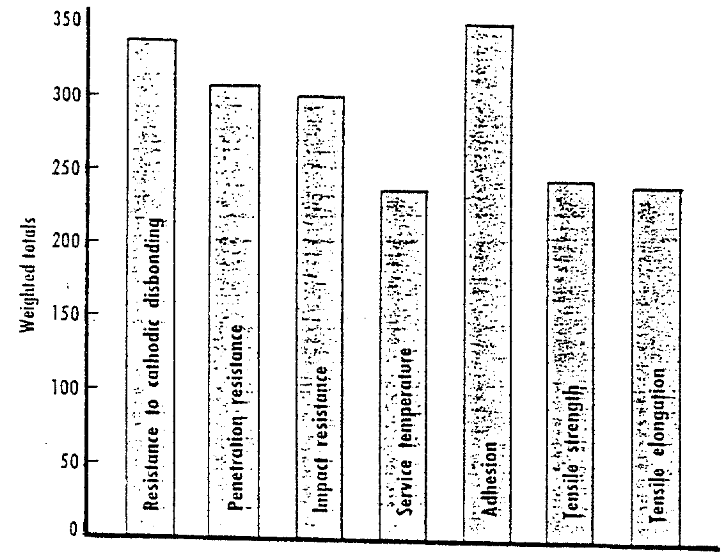
$$L(km) = \frac{313.766}{D^2} \qquad V(/km) = 3.187\ D^2$$

("D" is in inches.)

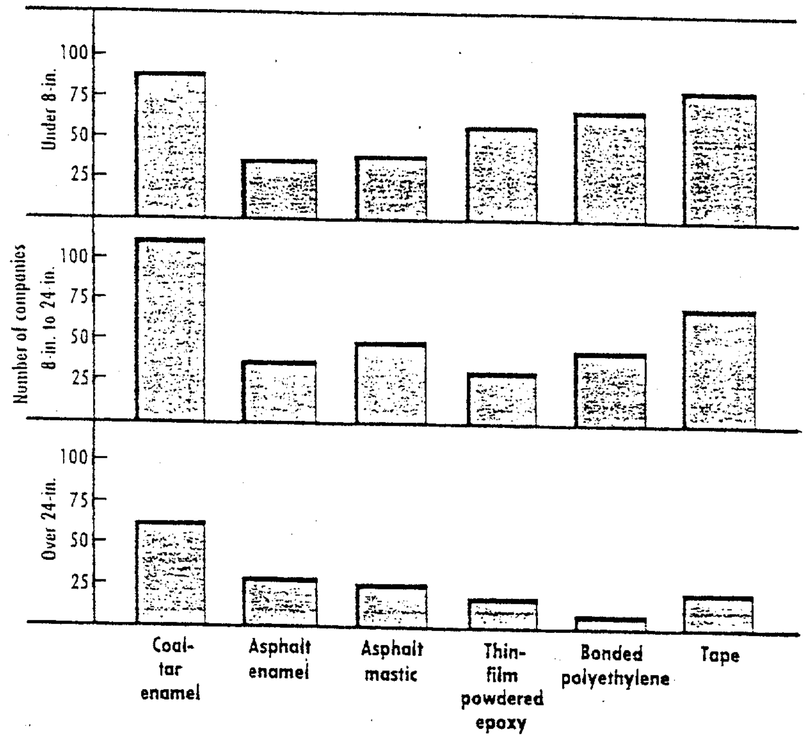
REF. F5

PIPELINE COATING SURVEY CHART 7-1

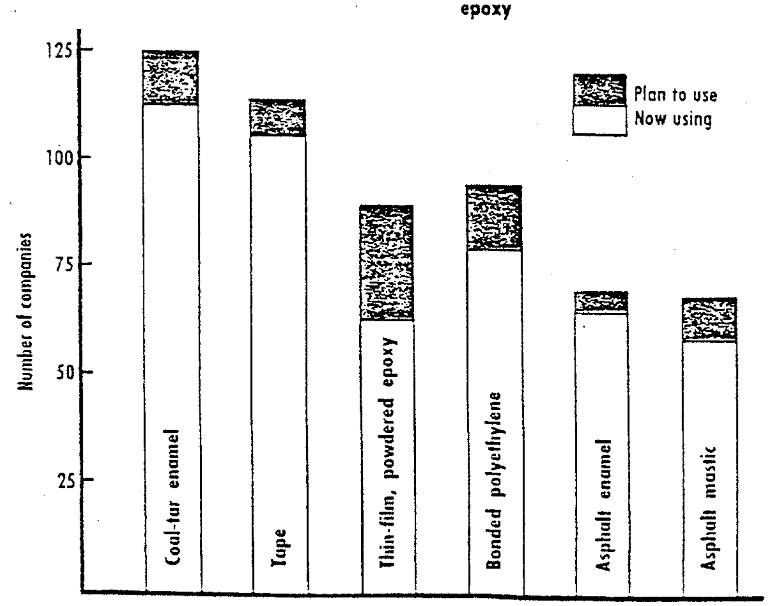
RATING



SIZES



USAGE



REF. 01

Significant factors for pipeline coatings

Factor	Type of coating: Epoxy powder	Poly-ethylene	Asphalt based	Coal-tar based
Thickness*	–	0	+	+
Adhesion (initial)	+	0	0	0
Resistance to disbonding*	0	–	0	0
Upper service temperature*	+	–	0	0
Lower service temperature*†	0	0	–	–
Lower service temperature*§	0	0	0	0
Impact resistance*†	0	+	0	0
Impact resistance*§	0	0	0	0
Elongation†	0	+	–	–
Elongation§	0	+	0	0
Tensile strength	+	+	0	0
Water permeability	0	0	0	0
Oxygen permeability	0	0	0	0
Resistance to biological attack	–	0	0	+
Abrasion resistance	0	0	0	0
Applicability	–	0	0	0
Compatibility with concrete§	–	0	0	0
Pipelaying*†	0	+	0	0
Pipelaying*§	0	0	0	0
Field joint coating†	0	0	0	0
Field joint coating§	0	0	+	+
Cathodic protection considerations*	0	–	0	0
Performance records*†	0	0	0	0
Performance records*§	0	0	+	+

*Selected factors of great importance. †Pipeline without concrete weight coating, onshore. §Pipeline with concrete weight coating, offshore.

Examples of published and estimated data for some physical parameters for pipeline coatings

Property	Coating type: Asphalt	Coal tar	Epoxy powder	Polyethylene
Normal thickness, mm	3-7 for enamels; 13-20 for mastics	3-7	0.3-0.5	2-4
Adhesion of newly applied coatings, approx. figures, MPa	2 estimated	>2 estimated	10-25	> 2 (peel values only)
Disbonding	variable records	variable records	variable records	susceptible
Upper service temperature limit (max. operation), °C.	60-80(90?)	60-80(90?)	90-100(120?)	60-70
Lower service temperature limit, °C.	−25?	−30?	−40?	−40?
Ultimate elongation, i.e., at break, %	2-5 estimated	2-5 estimated	2-6	500-600
Water vapor permeability, $10^{-8} gh^{-1} cm^{-1}$ Torr^{-1}	1.2	1.4 (for a poly-urethane tar)	0.3-1	0.06-0.3
Water penetration, % of thickness not penetrated	80-100	45-100	25-80	...
Oxygen permeability, $10^{-12} cm^2 s^{-1}$ Torr^{-1}		6 (for a poly-urethane tar)	0.5-0.8	10-27
Impact resistance, Nm	2-8	...	4-88	35-50
Tensile strength, MPa	2 estimated	...	50	15

REF. A19

CHART 7-3

NACE CURRENT REQUIREMENTS AND ANODE CAPACITY

Current Requirements for Cathodic Protection*

Area	Water Resistivity (ohm-cm)	Temperature	Turbulence	Typical Current Requirement ma/ft²
Gulf of Mexico	20	22	Moderate	5
U.S. West Coast	24	15	Moderate	7
Cook Inlet	50	2	Low	35
North Sea	26	12	High	10
Persian Gulf	15	30	Moderate	8
Indonesia	19	24	Moderate	5

*NACE Standard — RP-01-76, Pg 11

Amp-Hour Capacity Of Anodes*

Anode	Amp Hr/lb
Aluminum — zinc — mercury	1250-1290
Aluminum — zinc — indium	760-1090
Aluminum — zinc — tin	420-1180
Zinc (MIL-A-18001 H)	379
Magnesium (H1)	500

*NACE Standard — RP-01-76, Pg 11

REF. R6

CATHODIC PROTECTION

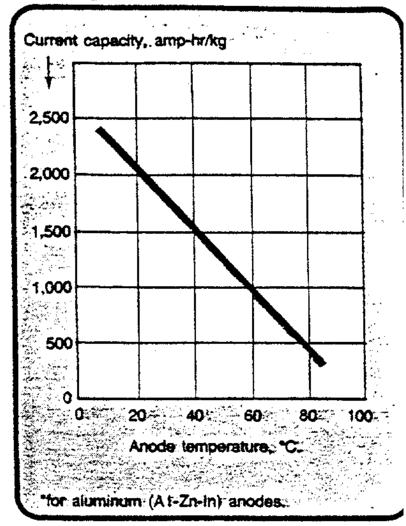
Composition of U.S. Mil. Spec. 18001 H

Metal	Composition, %
Aluminum	0.10 to 0.50
Cadmium	0.025 to 0.150
Iron	max. 0.005
Copper	max. 0.005
Lead	max. 0.006
Silicon	max. 0.125
Zinc	Remainder

Composition of modified zinc anode

Metal	Composition, %
Aluminum	0.1 to 0.2
Cadmium	0.03 to 0.06
Iron	max. 0.002
Copper	max. 0.005
Lead	max. 0.006
Zinc	Remainder

Design capacities*



*for aluminum (Al-Zn-In) anodes.

Potentials for cathodic protection of steel

Metal/Environment	Potential (v) vs. Ag/AgCl/ seawater reference electrode
Steel in aerobic environment	
• positive limit	−0.80
• negative limit	−1.05
Steel in anaerobic environment	
• positive limit	−0.90
• negative limit	−1.05

Minimum design current densities (ma/m²) for cathodic protection of bare steel[1]

	Initial value	Mean value	Final value
North Sea (northern)	160	120	100
North Sea (southern)	130	100	90
Arabian Gulf	120	90	80
India	120	90	80
Australia	120	90	80
Brazil	120	90	80
Gulf of Mexico	100	80	70
Western Africa	120	90	80
Indonesia	100	80	70
Pipelines (burial specified)	50	40	30
Risers in shafts with flowing seawater	180	140	120
Risers in shafts with stagnant seawater	120	90	80
Saline mud (ambient temperature)	25	20	15

Anode data for buried pipeline

Anode characteristics	Spacing (pipes/anode) 2	4
Weight, kg	160	320
Outer diameter, m	0.70	0.62
Length, m	0.35	1.4

Current capacities found for aluminum anodes in hot saline mud

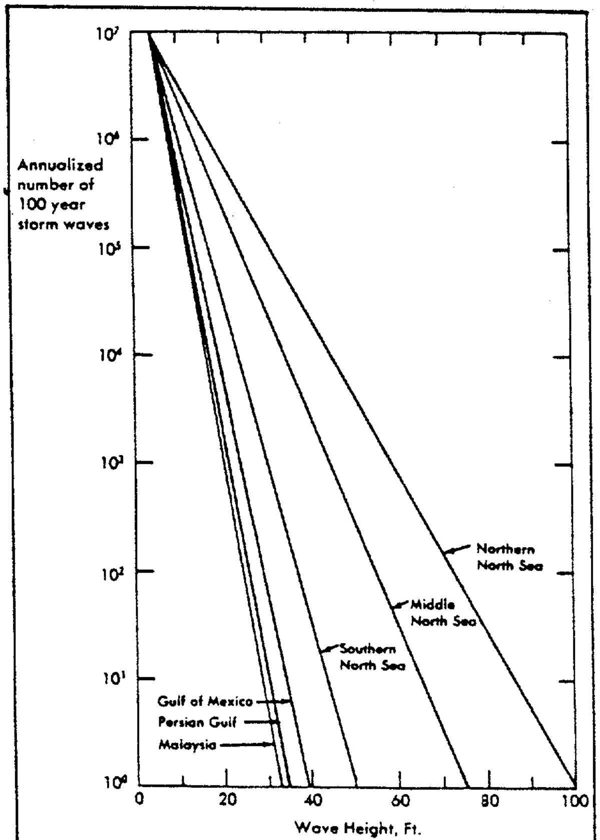
Publication	Anode (trade name)	Anode temperature, °C.	Test duration, months	Current capacity, amp-hr/kg
Houghton & Ashworth	Galvalum III*	Ambient (0-20)	6	2,730
	Galvalum III*	65-77	6/12	617/432
	Ba 778†	65-77	6/12	428/538
	Alanode§	65-77	6/12	348/-
Schrieber & Murray	Galvalum III*	Ambient	0.7-1.3	1,984
	Galvalum III*	38	0.7-1.3	1,984
	Galvalum III*	60	0.7-1.3	1,323
	Galvalum III*	82	0.7-1.3	880
Jensen, Rygh & Setre	Alanode§	80	1	466

*Galvalum is a trademark of The Dow Chemical Co.
†Ba 778 is a British Aluminium patented alloy.
§Alanode is a Mitsubishi Metal Corp. patented alloy.

Anode data for unburied pipeline

Anode characteristics	Spacing (pipes/anode) 3	6
Weight, kg	90	180
Outer diameter, m	0.64	0.59
Length, m	0.30	1.20

REF. M9



Annualized 100 Year Storm Waves

Design Criteria for 100 Year Storm

Storm Case Area	1 Malaysia	2 Persian Gulf	3 Gulf of Mexico	4 Southern North Sea	5 Middle North Sea	6 Northern North Sea
Maximum wave height, ft.	33	35	39	50	75	100
Maximum one minute wind gust, knot	62	53	74	100	100	100
Design Severity Compared To:						
Malaysia	1	0.92	1.15	1.56	1.83	2.08
Persian Gulf	1.09	1	1.25	1.70	2.00	2.27
Gulf of Mexico	0.87	0.80	1	1.36	1.60	1.82
Southern North Sea	0.64	0.59	0.73	1	1.17	1.33
Middle North Sea	0.54	0.50	0.63	0.86	1	1.14
Northern North Sea	0.48	0.44	0.55	0.75	0.88	1

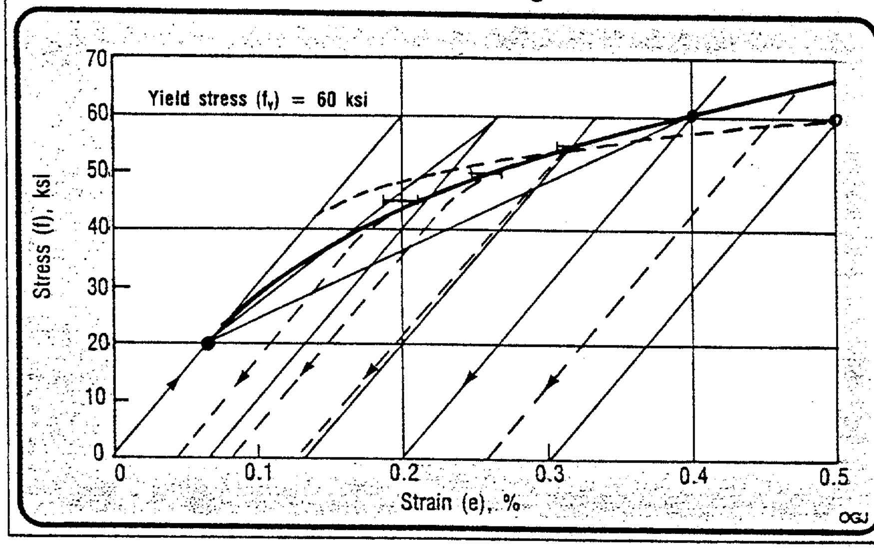
Annualized 100 Year Storm Wave Height Distribution

Wave Height, ft.

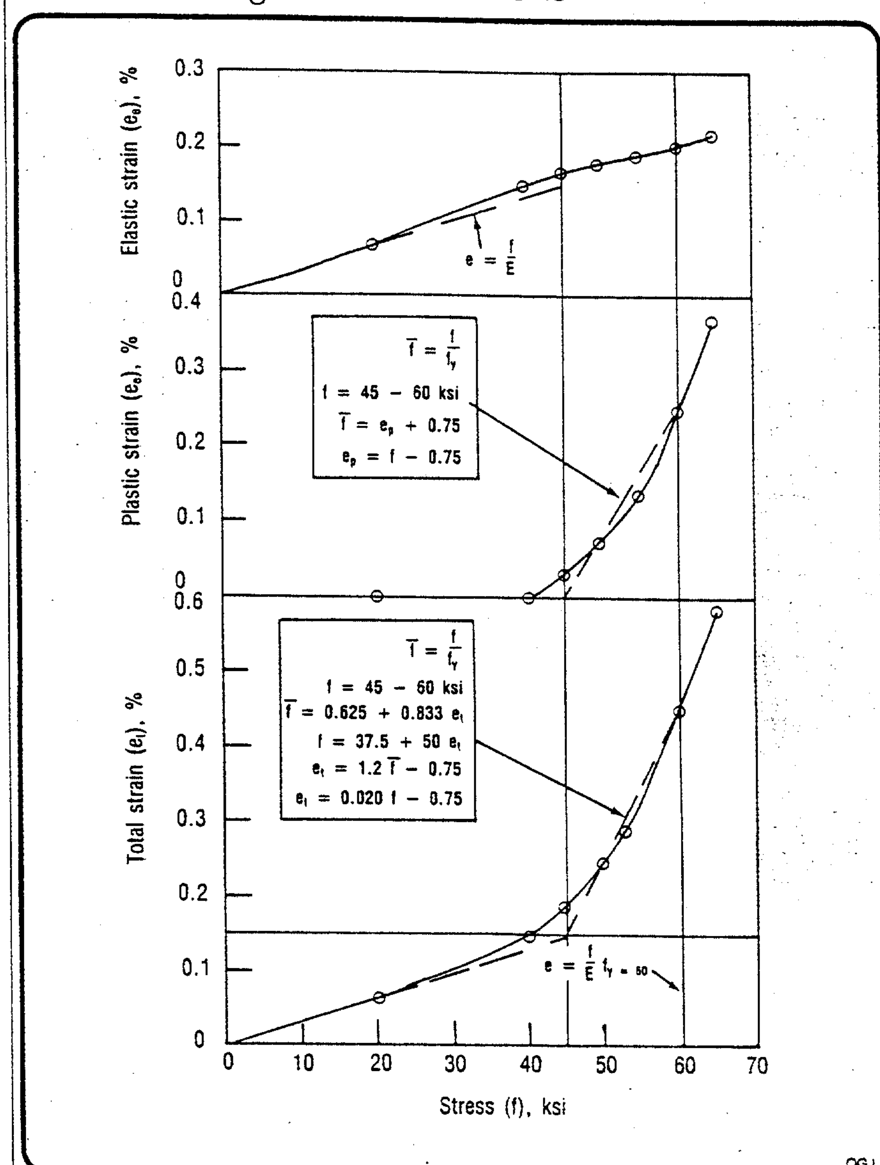
Number of Waves	Malaysia	Persian Gulf	Gulf of Mexico	Southern North Sea	Middle North Sea	Northern North Sea
10^7	4	4	4	4	4	4
10^6	8	9	9	10	14	18
10^5	12	13	14	17	24	31
10^4	16	17	19	22	34	45
10^3	21	22	24	30	44	59
10^2	25	26	29	37	55	73
10^1	29	30	34	44	65	86
10^0	33	35	39	50	75	100

Note: Assumes one 30 minute maximum storm at a single location in 100 years.

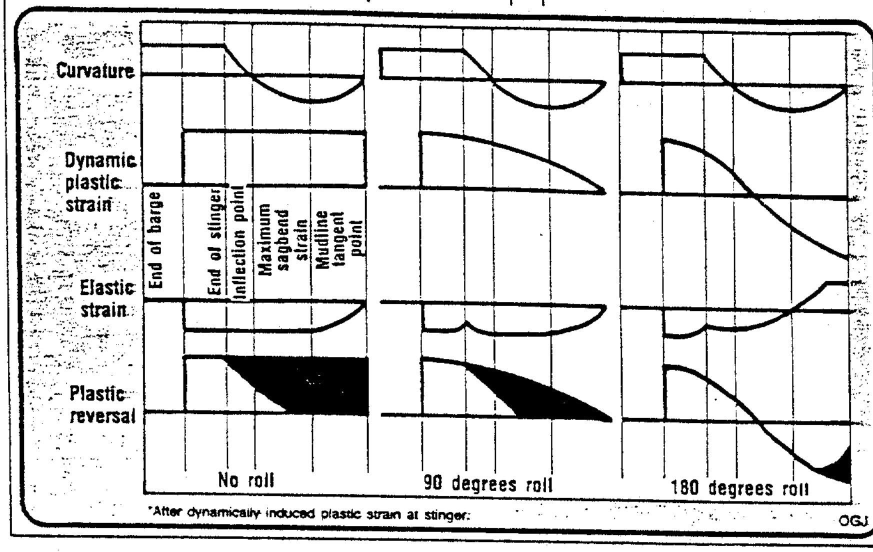
Constructed stress-strain diagram



Stress-average strain functions

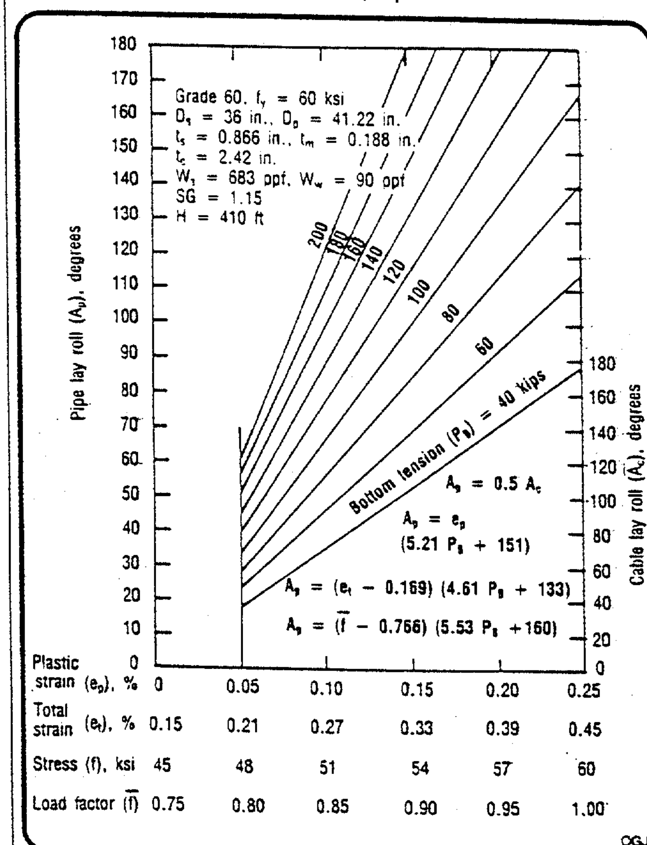


Plastic work in suspended pipeline*



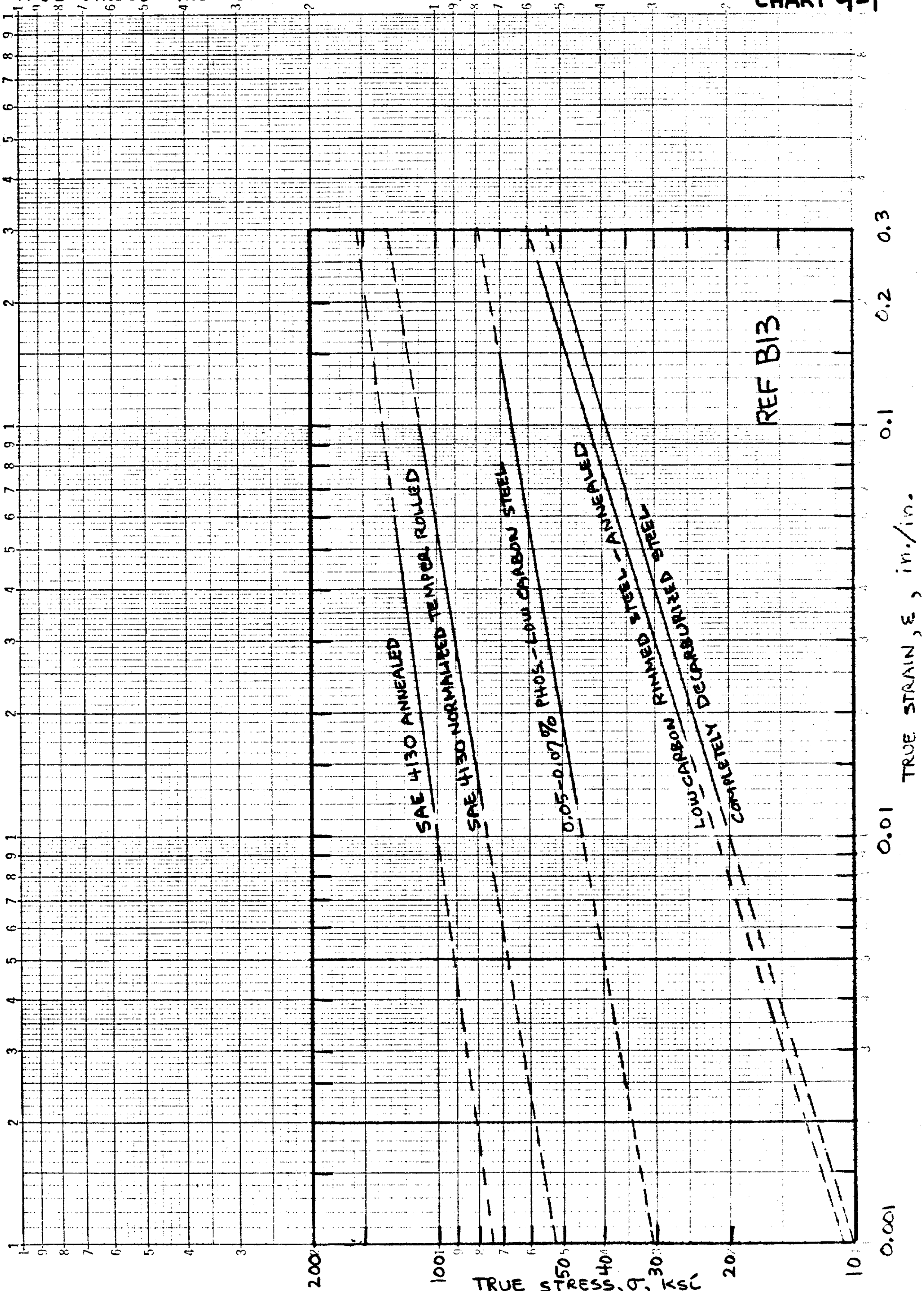
*After dynamically induced plastic strain at stinger.

Analyses chart for pipeline roll



TRUE STRESS – TRUE STRAIN VS STEEL TYPE

CHART 9-1



USING $\bar{\sigma} = K\bar{\varepsilon}^{n}$ PER REF B13

$n = \bar{\varepsilon}_u$ = STRAIN HARDENING COEFFICIENT

ENGINEERING OR NOMINAL VALUES: $\sigma = \dfrac{P}{A_i}$, $\varepsilon = \dfrac{L_f - L_i}{L_i} = \dfrac{L_f}{L_i} - 1$

WITH VOLUME CONSTANT IN PLASTICITY, $V_f = V_i$ OR $A_i L_i = A_f L_f$

THEREFORE TRUE STRESS IS: $\bar{\sigma} = \dfrac{P}{A_f} = \sigma\dfrac{A_i}{A_f} = \sigma\dfrac{L_f}{L_i} = \sigma(1+\varepsilon)$

TRUE STRAIN IS: $\bar{\varepsilon} = \displaystyle\int_{L_i}^{L_f}\frac{dL}{L} = \ln\frac{L_f}{L_i} = \ln(\varepsilon + 1)$

TO DETERMINE VALUE FOR n:

PLASTIC INSTABILITY AT $dP = 0$

$$P = \bar{\sigma} A_i \ , \ \bar{\varepsilon} = \ln\frac{A_i}{A_f} \Rightarrow A_i = A_o e^{-\bar{\varepsilon}}$$

$$P = \sigma A_i e^{-\bar{\varepsilon}}$$

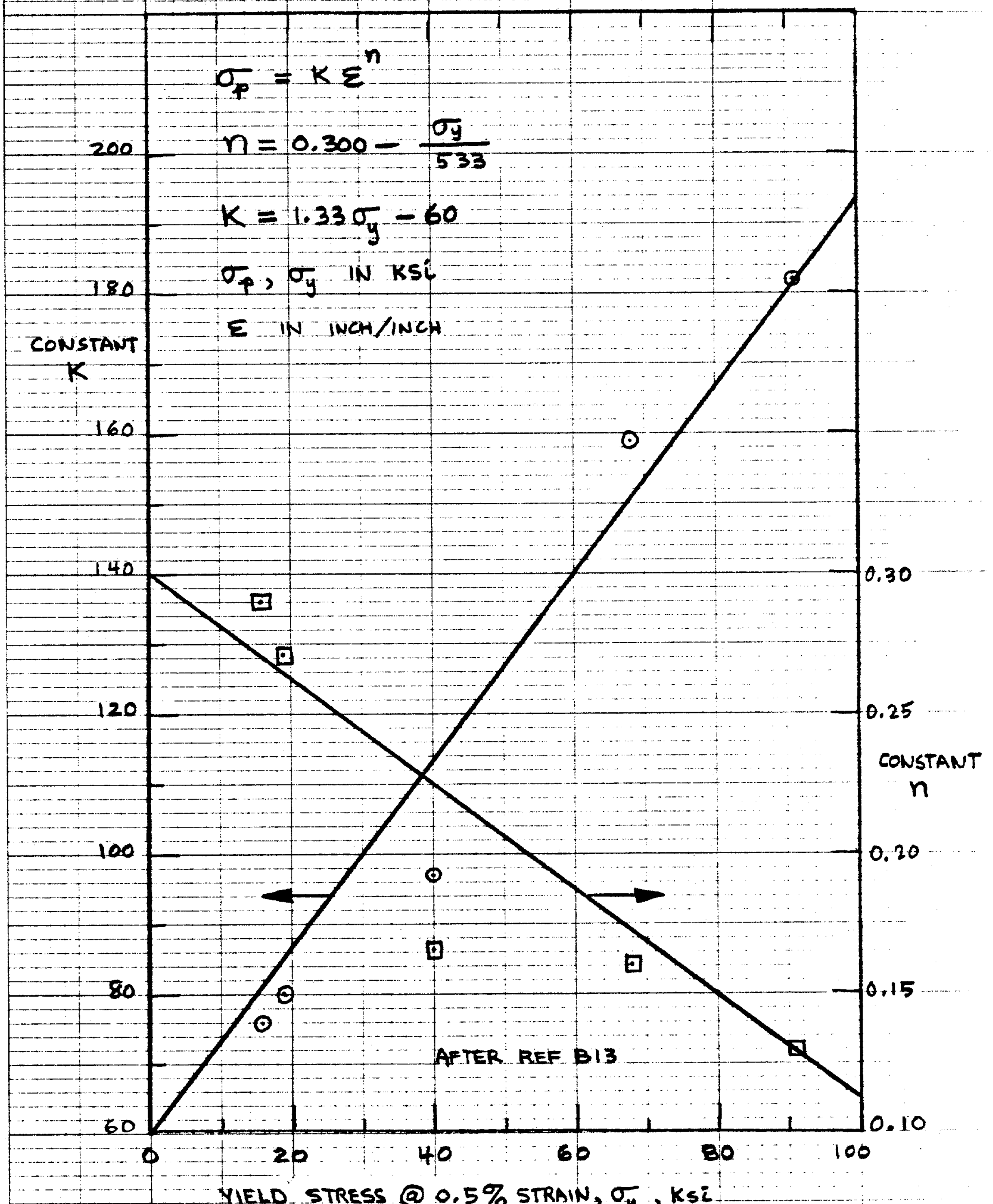
$$dP = A_i e^{-\bar{\varepsilon}}\, d\bar{\sigma} - \bar{\sigma} A_i e^{-\bar{\varepsilon}}\, d\bar{\varepsilon} = 0$$

$$\frac{d\bar{\sigma}}{d\bar{\varepsilon}} = \bar{\sigma} \quad @\ P_{MAX}$$

$$\bar{\sigma} = K\bar{\varepsilon}^{n} = \frac{d\bar{\sigma}}{d\bar{\varepsilon}} = Kn\bar{\varepsilon}^{n-1} \Rightarrow n = \bar{\varepsilon}_u$$

PLASTIC STRESS–STRAIN EQUATION FACTORS FOR STEEL

CHART 9-3



STRAIN HARDENING COEFFICIENT OF X65 STEEL

	REF. VI NOMINAL VALUES	TRUE VALUES
ULTIMATE STRESS, ksi	91.3	132
YIELD STRESS, ksi	70.2	70.5
ULTIMATE STRAIN, in./in.	0.443	0.366
YIELD STRAIN, in./in.	0.005	0.005

$$\bar{\sigma} = K \bar{\varepsilon}^{n}$$

$$\log \bar{\sigma} = \log K + n \log \bar{\varepsilon}$$

$$2.1205 = \log K + n(-0.4365)$$

$$1.1848 = \log K + n(-2.3010)$$

$$n = \frac{0.2723}{1.864} = 0.146$$ VS 0.17 FROM GENERAL GRAPH

VS 0.366 TRUE ULTIMATE STRAIN

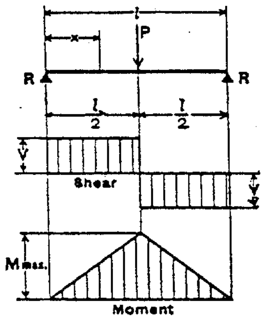
$$K = \frac{\bar{\sigma}}{\bar{\varepsilon}^{n}} = \frac{132}{0.366^{0.146}} = 152$$

CHART 10-1

BEAM DIAGRAMS AND FORMULAS

For various static loading conditions

A. SIMPLE BEAM—CONCENTRATED LOAD AT CENTER



Equivalent Tabular Load . . . . . . $= 2P$

$R = V$ . . . . $= \frac{P}{2}$

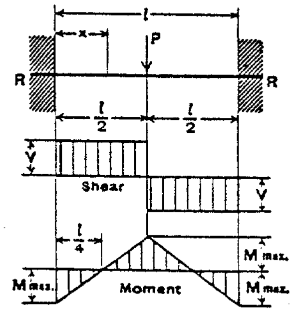
M max. (at point of load) . . . . . . $= \frac{Pl}{4}$

M_x (when $x < \frac{l}{2}$) . . . . . . $= \frac{Px}{2}$

Δmax. (at point of load) . . . . . . $= \frac{Pl^3}{48EI}$

Δx (when $x < \frac{l}{2}$) . . . . . . $= \frac{Px}{48EI}(3l^2 - 4x^2)$

B. BEAM FIXED AT BOTH ENDS—CONCENTRATED LOAD AT CENTER



Equivalent Tabular Load . . . . . $= P$

$R = V$ . . . . $= \frac{P}{2}$

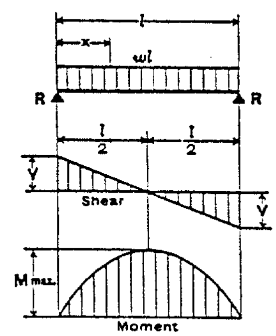
M max. (at center and ends) . . . . $= \frac{Pl}{8}$

M_x (when $x < \frac{l}{2}$) . . . . . . $= \frac{P}{8}(4x - l)$

Δmax. (at center) . . . . $= \frac{Pl^3}{192EI}$

Δx (when $x < \frac{l}{2}$) . . . . . . $= \frac{Px^2}{48EI}(3l - 4x)$

C. SIMPLE BEAM—UNIFORMLY DISTRIBUTED LOAD



Equivalent Tabular Load . . . . $= wl$

$R = V$ . . . . $= \frac{wl}{2}$

V_x . . . . $= w\left(\frac{l}{2} - x\right)$

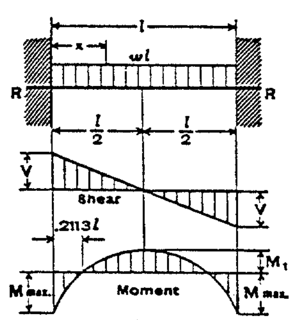
M max. (at center) . . . . . $= \frac{wl^2}{8}$

M_x . . . . $= \frac{wx}{2}(l - x)$

Δmax. (at center) . . . . . $= \frac{5wl^4}{384EI}$

Δx . . . . $= \frac{wx}{24EI}(l^3 - 2lx^2 + x^3)$

D. BEAM FIXED AT BOTH ENDS—UNIFORMLY DISTRIBUTED LOADS



Equivalent Tabular Load . . . . . $= \frac{2wl}{3}$

$R = V$ . . . . $= \frac{wl}{2}$

V_x . . . . $= w\left(\frac{l}{2} - x\right)$

M max. (at ends) . . . . . . $= \frac{wl^2}{12}$

M_1 (at center) . . . . $= \frac{wl^2}{24}$

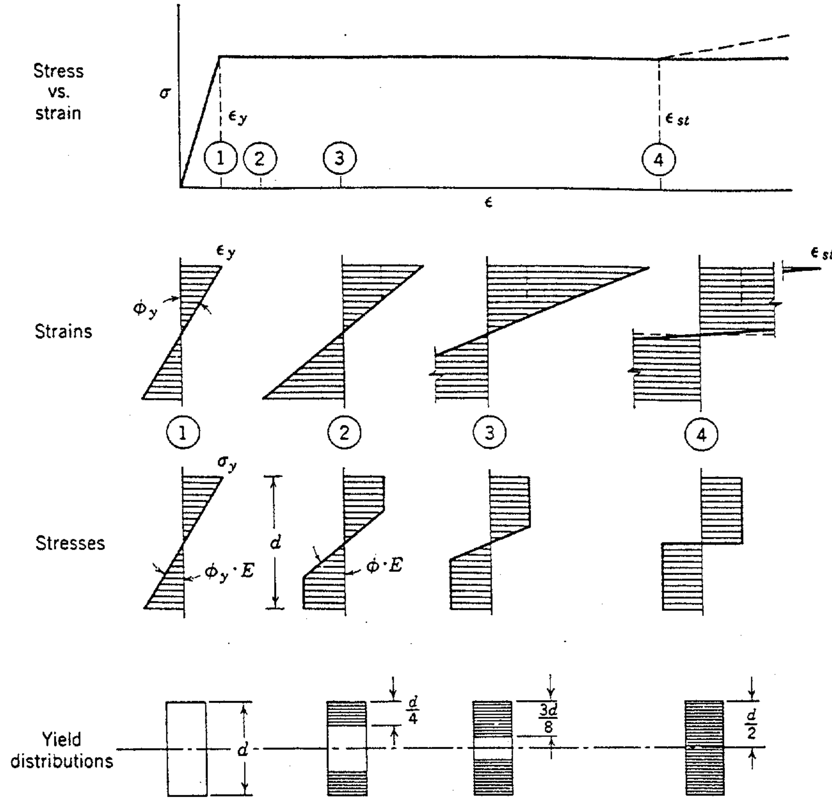
M_x . . . . $= \frac{w}{12}(6lx - l^2 - 6x^2)$

Δmax. (at center) . . . . $= \frac{wl^4}{384EI}$

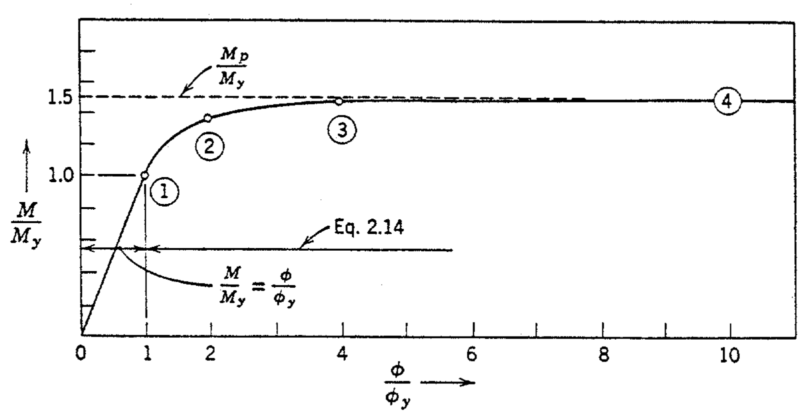
Δx . . . . $= \frac{wx^2}{24EI}(l - x)^2$

REF. A18

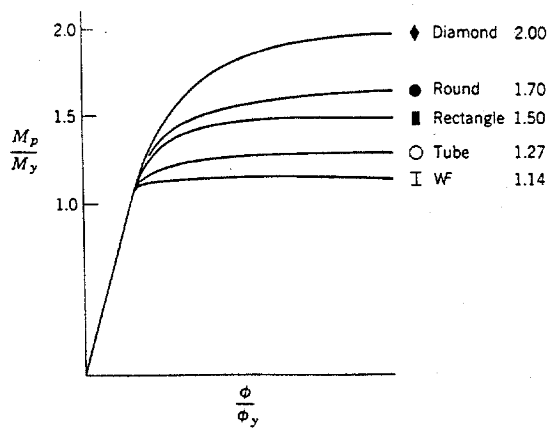
PLASTIC STRAIN PROGRESSION AND SHAPE FACTORS



Plastic bending of rectangular beam.



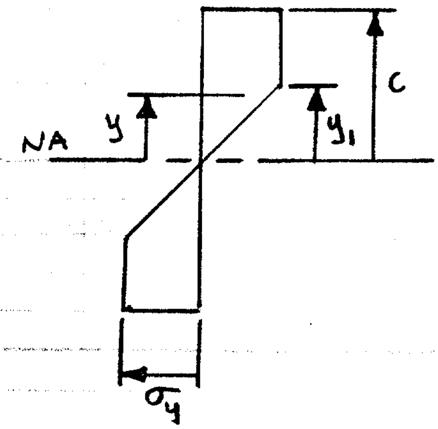
Nondimensional moment–curvature relationship for rectangular beam.



Variation in the shape factor for various cross-sectional forms.

PLASTIC MOMENT DERIVATION

CHART 10-3



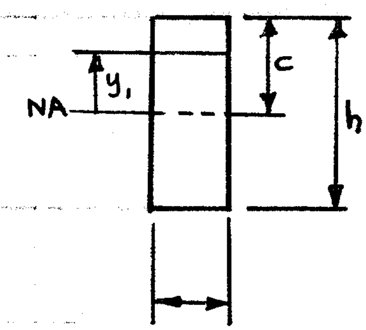
WHEN $y < y_1$, $\frac{\sigma}{y} = \frac{\sigma_y}{y_1} \Rightarrow \sigma = \frac{y}{y_1}\sigma_y$

WHEN $y > y_1$, $\sigma = \sigma_y = C$

$$M = \int \sigma y \, dA = 2\int_0^{y_1} \frac{y}{y_1}\sigma_y y \, dA + 2\int_{y_1}^{c} \sigma_y y \, dA$$

$$= 2\frac{\sigma_y}{y_1}\int_0^{y_1} y^2 \, dA + 2\sigma_y \int_{y_1}^{c} y \, dA$$

FOR A RECTANGULAR SECTION,



$$M = 2\frac{\sigma_y}{y_1}\left(\frac{b y_1^3}{3}\right) + 2\sigma_y b(c - y_1)\left(\frac{c + y_1}{2}\right)$$

$$= \sigma_y \left(bc^2 - \frac{b}{3} y_1^2\right)$$

FOR A FULLY PLASTIC MOMENT, $y_1 = 0$ AND

$$M_p = bc^2 \sigma_y = \frac{bh^2}{4}\sigma_y$$

MAXIMUM ELASTIC MOMENT, $M_e = Z_e \sigma = \frac{bh^2}{6}\sigma_y$

THEREFORE $\frac{M_p}{M_e} = 1.5$

UNIFORMLY LOADED, FIXED END BEAM

TO LOCATE ZERO MOMENT :

$$M_x = \frac{w}{12}(6Lx - L^2 - 6x^2) = 0 \Rightarrow 6x^2 - 6Lx + L^2 = 0$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \frac{6L \pm \sqrt{36L^2 - 4(6)L^2}}{2(6)} = \frac{6L \pm L\sqrt{12}}{12} = 0.5L \pm 0.288L = 0.212L, 0.788L$$

TO LOCATE $\frac{2}{3} M_{MAX}$:

$$M_x = \frac{w}{12}(6Lx - L^2 - 6x^2) = \frac{2}{3}M_m = -\frac{2}{3}\frac{wL^2}{12} \Rightarrow 6x^2 - 6Lx + \frac{L^2}{3} = 0$$

$$x = \frac{6L \pm \sqrt{36L^2 - 4(6)(\frac{1}{3})L^2}}{2(6)} = 0.5L \pm 0.440L = 0.060L, 0.940L$$

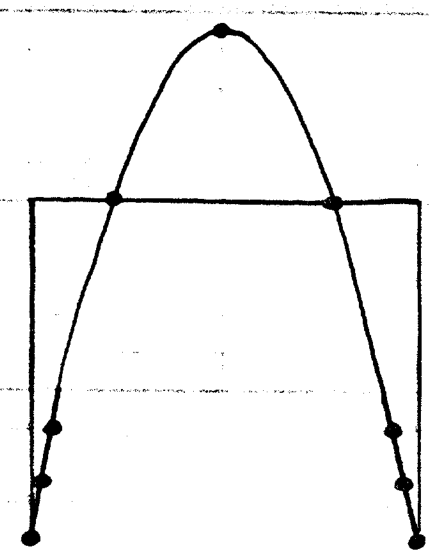
TO LOCATE $\frac{5}{6} M_{MAX}$:

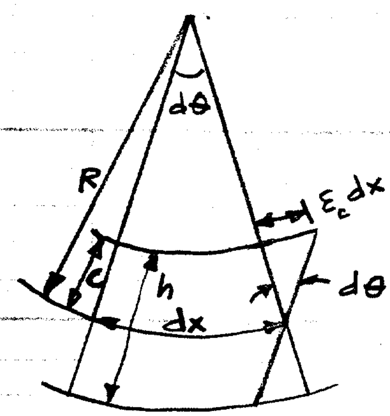
$$6Lx - L^2 - 6x^2 = -\frac{5}{6}L^2 \Rightarrow x = \frac{6L \pm \sqrt{36L^2 - 24\frac{L^2}{6}}}{12} = 0.5 \pm 0.471 = 0.029L, 0.971L$$

MOMENT VS LOCATION RATIOS :

$$\frac{\Delta \frac{1}{6} M_{MAX}}{\Delta \frac{1}{3} M_{MAX}} = 2 \approx \frac{x_{1/3}}{x_{1/6}} = \frac{0.060}{0.029}$$

THEREFORE APPROXIMATELY LINEAR MOMENT FROM $M = \frac{2}{3} M_{MAX}$ TO FIXED END.





STRAIN RATIOS, $\dfrac{\varepsilon_c}{c} = \dfrac{\varepsilon_y}{y_1}$

FROM GEOMETRY, $\phi = \dfrac{1}{R} = \dfrac{d\theta}{dx} = \dfrac{\varepsilon_c}{c} = \dfrac{\varepsilon_y}{y_1} = \dfrac{\sigma_y}{E y_1}$

SINCE $\sigma_y = E\varepsilon_y = \dfrac{M_y c}{I}$

$$M = \frac{\sigma_y}{y_1}\left(bc^2 - \frac{b}{3}y_1^2\right)y_1$$

$$\frac{d\theta}{dx} = \frac{\sigma_y}{E y_1} = \frac{M}{E y_1\left(bc^2 - \frac{b}{3}y_1^2\right)} = \frac{M}{E b y_1\left(c^2 - \frac{y_1^2}{3}\right)} = \frac{1}{R}$$

COMBINING ABOVE RELATIONS (SEE P.29, REF B14 OR P.147, REF N5)

$$M = \sigma_y\left[bc^2 - \frac{b}{3}\left(\frac{\sigma_y R}{E}\right)^2\right] \quad \text{OR} \quad \frac{M}{M_y} = \frac{3}{2}\left[1 - \frac{1}{3}\left(\frac{R}{R_y}\right)^2\right]$$

ALTERNATELY $R = \dfrac{EI}{M_y}\sqrt{3 - \dfrac{2M}{M_y}}$

EQUATIONS OF ELASTICITY

IN TERMS OF STRESS:

$$\varepsilon_x = \frac{1}{E}\left[\sigma_x - \mu(\sigma_y + \sigma_z)\right] \qquad \gamma_{xy} = \frac{\tau_{xy}}{G}$$

$$\varepsilon_y = \ldots \qquad \gamma_{yz} =$$

$$\varepsilon_z = \ldots \qquad \gamma_{zx} =$$

OR IN TERMS OF STRAIN:

$$\sigma_x = \frac{\mu E}{(1+\mu)(1-2\mu)} e + \frac{E}{1+\mu}\varepsilon_x \qquad \tau_{xy} = G\gamma_{xy}$$

$$\sigma_y = \ldots$$

$$\sigma_z = \ldots$$

IN THE CASE OF PLANE STRESS, $\sigma_z = \tau_{yz} = \tau_{zx} = 0$, AND

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \mu\sigma_y) \qquad \sigma_x = \frac{E}{1-\mu^2}(\varepsilon_x + \mu\varepsilon_y)$$

$$\varepsilon_y = \frac{1}{E}(\sigma_y - \mu\sigma_x) \qquad \sigma_y = \frac{E}{1-\mu^2}(\varepsilon_y + \mu\varepsilon_x)$$

$$\varepsilon_z = -\frac{\mu}{E}(\sigma_x + \sigma_y)$$

$$\gamma_{xy} = \frac{\tau_{xy}}{G} \qquad \tau_{xy} = G\gamma_{xy}$$

IN THE CASE OF PLANE STRAIN, $\varepsilon_z = \gamma_{yz} = \gamma_{zx} = 0$, AND

$$\sigma_x = \frac{E}{(1+\mu)(1-2\mu)}\left[(1-\mu)\varepsilon_x + \mu\varepsilon_y\right] \qquad \varepsilon_x = \frac{1+\mu}{E}\left[(1-\mu)\sigma_x - \mu\sigma_y\right]$$

$$\sigma_y = \frac{E}{(1+\mu)(1-2\mu)}\left[\mu\varepsilon_x + (1-\mu)\varepsilon_y\right] \qquad \varepsilon_y = \frac{1+\mu}{E}\left[(1-\mu)\sigma_y - \mu\sigma_x\right]$$

$$\sigma_z = \frac{\mu E}{(1+\mu)(1-2\mu)}(\varepsilon_x + \varepsilon_y)$$

$$\tau_{xy} = G\gamma_{xy} \qquad \gamma_{xy} = \frac{\tau_{xy}}{G}$$

WHERE $e = \varepsilon_x + \varepsilon_y + \varepsilon_z$ AND $G = \frac{E}{2(1+\mu)}$

EQUATIONS FOR ELASTIC STRAIN ENERGY

FOR THREE DIMENSIONAL STRESS:

$$U = \frac{1}{2} \iiint_V (\sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \sigma_z \varepsilon_z + \tau_{xy} \gamma_{xy} + \tau_{yz} \gamma_{yz} + \tau_{zx} \gamma_{zx})\, dx\, dy\, dz$$

OR IN TERMS OF STRESS COMPONENTS ONLY:

$$U = \iiint_V \left[\frac{1}{2E} (\sigma_x^2 + \sigma_y^2 + \sigma_z^2) - \frac{\mu}{E} (\sigma_x \sigma_y + \sigma_y \sigma_z + \sigma_z \sigma_x) + \frac{1}{2G} (\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2) \right] dx\, dy\, dz$$

OR IN TERMS OF STRAIN COMPONENTS ONLY:

$$U = \frac{E}{2(1+\mu)} \iiint_V \left[\frac{\mu}{1-2\mu} e^2 + (\varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2) + \frac{1}{2} (\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2) \right] dx\, dy\, dz$$

IN THE CASE OF PLANE STRESS, $\sigma_z = \tau_{yz} = \tau_{zx} = 0$ AND

$$U = \frac{1}{2} \iiint_V \left[\frac{1}{E} (\sigma_x^2 + \sigma_y^2 - 2\mu \sigma_x \sigma_y + \frac{1}{G} \tau_{xy}^2 \right] dx\, dy\, dz \quad \text{OR}$$

$$U = \frac{E}{2(1+\mu)} \iiint_V \left[\frac{1}{1-\mu} (\varepsilon_x^2 + \varepsilon_y^2 + 2\mu \varepsilon_x \varepsilon_y) + \frac{1}{2} \gamma_{xy}^2 \right] dx\, dy\, dz$$

PLASTIC STRAIN ENERGY WITH STRAIN HARDENING

$$\mathcal{E} = 4 \iiint_V \sigma \varepsilon \, dx\, dy\, dz$$

IF UNIT DEPTH AND $\sigma_p = K \varepsilon^n$

$$\mathcal{E} = 4K \iint_{x\,y} \varepsilon^{n+1} \, dx\, dy = 4K\left(\frac{\varepsilon_m}{c}\right)^{n+1} \int_{x=0}^{x_0} \int_{y=\frac{t}{2}\sqrt{\frac{x}{x_0}}}^{c} \left(1-\frac{x^2}{x_0^2}\right)^{n+1} y^{n+1} \, dx\, dy$$

$$= 4K\left(\frac{2\varepsilon_m}{t}\right)^{n+1} \int_{x=0}^{x_0} \left(1-\frac{x^2}{x_0^2}\right)^{n+1} \left.\frac{y^{n+2}}{n+2}\right|_{y=\frac{t}{2}\sqrt{\frac{x}{x_0}}}^{c} dx$$

$$= \frac{4K}{n+2}\left(\frac{2\varepsilon_m}{t}\right)^{n+1} \int_{x=0}^{x_0} \left(1-\frac{x^2}{x_0^2}\right)^{n+1} \left(c^{n+2} - \left[\frac{t}{2}\sqrt{\frac{x}{x_0}}\right]^{n+2}\right) dx$$

$$= \frac{4K}{n+2}\left(\frac{2\varepsilon_m}{t}\right)^{n+1} \int_{x=0}^{x_0} \left\{ c^{n+2}\left(1-\frac{x^2}{x_0^2}\right)^{n+1} - \left(\frac{t^2}{4}\frac{x}{x_0}\right)^{\frac{n+2}{2}} \left(1-\frac{x^2}{x_0^2}\right)^{n+1} \right\} dx$$

TO INTEGRATE, USE BINOMIAL EXPANSION:

$$(1 \pm v)^m = 1 \pm mx + \frac{m(m-1)}{2!} v^2 \pm \frac{m(m-1)(m-2)}{3!} v^3 + \cdots$$

SUBSTITUTE $v = \frac{x^2}{x_0^2}$, $m = n+1$ INTO EXPANSION, MULTIPLY TERMS,

COMBINE UNITS, THEN INTEGRATE OVER LIMITS.

VON MISES FAILURE CRITERIA

FOR AN ELASTIC TRIAXIAL STRESS STATE:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\,\sigma_{yu}^2$$

OR IN TERMS OF STRAIN:

$$(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 = 2\,(1+\mu)^2\,\varepsilon_{yu}^2$$

FOR ELASTIC ANALYSES, POISSONS RATIO, μ, IS 0.3 AND

$$(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 = 3.38\,\varepsilon_{yu}^2$$

FOR PLASTIC ANALYSES, POISSONS RATIO, μ, IS 0.5 AND

$$(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 = 4.50\,\varepsilon_{yu}^2$$

$$\frac{\text{PLASTIC}}{\text{ELASTIC}} = \frac{4.50}{3.38} = 1.33$$

VON MISES BIAXIAL EFFECT ON COLLAPSE FAILURE STRESS **CHART 12-2**

HUBER-VON MISES-HENCKY MAXIMUM ENERGY OF DISTORTION FAILURE THEORY :

$$(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2=2\,\sigma_y^{\,2}$$

THE RADIAL STRESS IS NEGLIGIBLE, i.e.

$$\sigma_3=-p\ ,\quad \frac{\sigma_3}{\sigma_1}\approx 0$$

FOR A SECTION OF PIPE WITH UNRESTRAINED ENDS : $\varepsilon_\ell=-\mu\,\varepsilon_h$

THEN FOR A PIPE WITH RESTRAINED ENDS : $\sigma_2=\mu\,\sigma_1$

SO $(\sigma_1-\mu\sigma_1)^2+(-\mu\sigma_1)^2+\sigma_1^{\,2}=2\,\sigma_y^{\,2}$

USING POISSONS RATIO OF $\mu=0.3$: $0.79\,\sigma_1=\sigma_y$ OR $\sigma_1=1.26\,\sigma_y$

SO THE ALLOWABLE PRESSURE BY VON MISES IS ABOUT 26 % GREATER THAN CALCULATIONS BY PLANE STRESS ANALYSES.

PER TIMOSHENKO FORMULAS (REF. T4) FOR BUCKLING OF THIN TUBES:

FOR EXTERNAL PRESSURE ONLY, $p_c = \frac{2E}{1-\mu^2}\left(\frac{t}{D}\right)^3$

FOR COLUMN BUCKLING ONLY, $\sigma_c = \frac{2Et}{D\sqrt{3(1-\mu^2)}}$

IF $\mu = 0.3$ THEN $p_c = 2.20\,E\left(\frac{t}{D}\right)^3$; $\sigma_c = 1.21\,E\left(\frac{t}{D}\right)$

BY AISC PROPORTIONALITY: $\frac{p}{p_c} + \frac{\sigma}{\sigma_c} = 1$

DUE TO RESTRAINT OF A PIPELINE TO FREELY EXPAND LONGITUDIONALLY,

$$\sigma = E\mu\varepsilon_h = \mu\sigma_h = \mu\frac{pD}{2t} = 0.15\,p\left(\frac{D}{t}\right)$$

$$1 = \frac{p}{p_c} + \frac{0.15\,p\left(\frac{D}{t}\right)}{1.21\,E\left(\frac{t}{D}\right)} = \frac{p}{p_c}\left[1 + \frac{0.15\,\frac{D}{t}(2.20)E\left(\frac{t}{D}\right)^3}{1.21\,E\,\frac{t}{D}}\right] = \frac{p}{p_c}\left[1 + 0.272\,\frac{t}{D}\right]$$

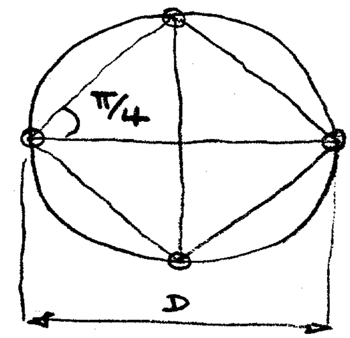
IF FOR EXAMPLE $\frac{D}{t} = \frac{36}{0.866} = 41.5$, $p = 0.993\,p_c$

THEREFORE LONGITUDIONAL RESTRAINT CAUSING BIAXIAL LOADS HAS NEGLIGIBLE EFFECT ON THE ELASTIC COLLAPSE PRESSURE.

PROPAGATION PRESSURE, EIGHT COLLAPSE

$360° = 2\pi$ radians $\Rightarrow 45° = \frac{\pi}{4}$

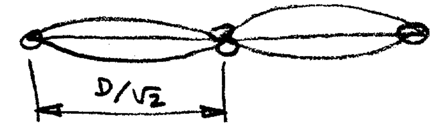
$\Delta\theta = 8\,\frac{\pi}{4} = 2\pi$



EXTERNAL WORK = $P_p \Delta V$ = ENERGY/UNIT LENGTH = W_e

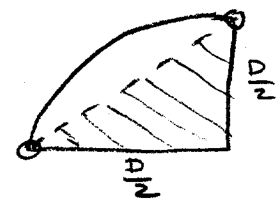
$A_i = \pi D^2/4$

$A_f = A_i - 4\,\frac{1}{2}\,\frac{D}{2}\,\frac{D}{2} = A_i - \frac{D^2}{2}$



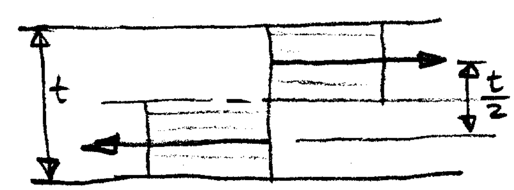
$\Delta A = A_i - A_f = \frac{D^2}{2} = \Delta V/L$

$W_e = \frac{P D^2}{2}$



DISSIPATED ENERGY = $E_d = M\,\Delta\theta$

$M = \left(\sigma \frac{t}{2}\right)\left(\frac{t}{2}\right) = \frac{\sigma t^2}{4}$



$E_d = \left(\frac{\sigma t^2}{4}\right)(2\pi) = \frac{\sigma t^2 \pi}{2}$

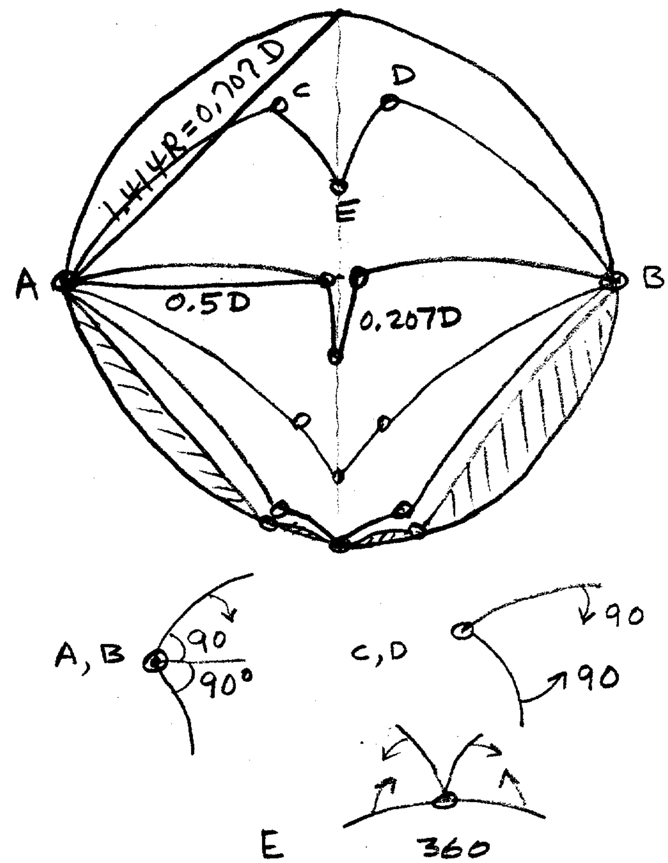
$E_d = W_e$

$\frac{\sigma t^2 \pi}{\cancel{2}} = \frac{P_p D^2}{\cancel{2}}$

$P_p = \pi \sigma \frac{t^2}{D^2}$

PROPAGATION PRESSURE — NEST COLLAPSE

$$W_e = P\Delta V = P\pi\frac{D^2}{4}$$



$$W_d = M\Delta\theta$$

$$M = \left(\sigma\frac{t}{2}\right)\frac{t}{2} = \frac{\sigma t^2}{4}$$

$$\Delta\theta = 2(180) + 2(180) + 360 = 3(360^\circ)$$

$$= 3\,(2\pi) = 6\pi$$

$$W_d = \frac{\sigma t^2}{4}\,6\pi = \frac{3}{2}\pi\sigma t^2$$

$$W_e = W_d$$

$$\frac{P\cancel{\pi}D^2}{K4} = \frac{3}{2}\cancel{\pi}\sigma t^2$$

$$P = K\frac{4}{D^2}\,\frac{3}{2}\,\sigma t^2 = K6\sigma\left(\frac{t}{D}\right)^2$$

SINCE $\Delta V < \frac{\pi D^2}{4}$, $K > 1$

$$P_{NP} \doteq 2\pi\sigma\left(\frac{t}{D}\right)^2$$

1. FLAGGS LINE, NORTH SEA

$H = 500\text{ ft.},\ \sigma_y = 60\text{ ksi},\ D = 36.0\text{ in.},\ t = 0.866\text{ in.},\ \frac{D}{t} = 41.5$

$$p_w = \gamma H = \frac{64.4}{144}(500) = 223\text{ psi}$$

$$p_c = \frac{2E}{1-\mu^2}\left(\frac{t}{D}\right)^3 = \frac{2.19(3^{7})}{0.714^{5}} = 920\text{ psi}$$

$$p_p = \pi\sigma_y\left(\frac{t}{D}\right)^2 = 3.14\frac{(6^{4})}{1.72^{3}} = 109\text{ psi}$$

$$\frac{p_c}{p_p} = \frac{920}{109} = 8.44$$

2. COGNAC LINE, GULF OF MEXICO

$H = 1000\text{ ft.},\ \sigma_y = 46\text{ ksi},\ D = 12.75\text{ in.},\ t = 0.625,\ \frac{D}{t} = 20.4$

$p_w = 444,\ p_c = 7670,\ p_p = 347,\ \frac{p_c}{p_p} = 22.1$

EXTERNAL WORK FUNCTION

WORK AT EACH END OF FIXED BEAM IS MOMENT TIMES ANGLE, THEREFORE

$$W = 2 M_p \theta$$

$$= 2 \sigma_y Z_p \theta$$

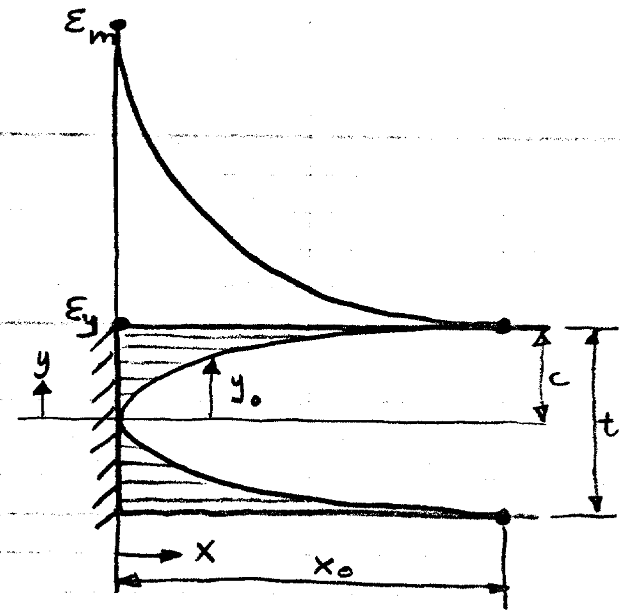
$$= 2 \sigma_y \frac{bd^2}{4} 45°$$

$$= 2 \sigma_y (1) \frac{t^2}{4} \frac{\pi}{4}$$

$$= 0.392 \sigma_y t^2$$

PLASTIC STRAIN VARIATION NEAR HINGE

$$\frac{M}{M_p} = \frac{\sigma_y\left[\frac{bt^2}{4} - \frac{by_o^2}{3}\right]}{\sigma_y \frac{bt^2}{4}} = 1 - \frac{4}{3}\frac{y_o^2}{t^2} \text{, PARABOLIC}$$



TO GET VARIATION OF $y_o(x)$:

$$x = ay_o^2 = x_o = a\left(\frac{t}{2}\right)^2 \Rightarrow a = \frac{4x_o}{t^2}$$

$$y_o = \sqrt{\frac{x}{a}} = \sqrt{\frac{xt^2}{x_o 4}} = \frac{t}{2}\sqrt{\frac{x}{x_o}}$$

TO GET VARIATION OF $\varepsilon_c(x)$:

$$\varepsilon_c = a + bx^2, \quad \varepsilon_m = a + b(0), \quad a = \varepsilon_m$$

$$\varepsilon_y = a + bx_o^2, \quad b = \frac{\varepsilon_y - \varepsilon_m}{x_o^2}$$

$$\Rightarrow \varepsilon_c = \varepsilon_m + \frac{\varepsilon_y - \varepsilon_m}{x_o^2}x^2$$

TO GET VARIATION OF $\varepsilon(y)$:

$$\frac{\varepsilon_c}{\varepsilon_o} = \frac{c}{y_o} = \frac{\varepsilon_c}{\varepsilon} = \frac{c}{y} \Rightarrow \varepsilon = \frac{y}{c}\varepsilon_c$$

COMBINING ABOVE : $\varepsilon(x,y) = \left(\varepsilon_m + \frac{\varepsilon_y - \varepsilon_m}{x_o^2}x^2\right)\frac{y}{c}$

SINCE $\frac{\varepsilon_y}{\varepsilon_m} \approx 0$ THEN USE $\varepsilon(x,y) = \varepsilon_m\left(1 - \frac{x^2}{x_o^2}\right)\frac{y}{c}$

$$\mathcal{E} = \iiint_V \sigma \varepsilon \, dx\, dy\, dz$$

INTEGRATING OVER ONE HALF OF ONE END OF BEAM OF UNIT DEPTH :

$$\mathcal{E} = 4\sigma_y \int_{x=0}^{x_0} \int_{y=\frac{t}{2}\sqrt{\frac{x}{x_0}}}^{c} \varepsilon_m \left(1 - \frac{x^2}{x_0^2}\right) \frac{y}{c} \, dx\, dy$$

$$= 4\sigma_y \varepsilon_m \int_{x=0}^{x_0} \left(1 - \frac{x^2}{x_0^2}\right) \frac{y^2}{2c} \Bigg|_{y=\frac{t}{2}\sqrt{\frac{x}{x_0}}}^{c} dx$$

$$= 2\sigma_y \frac{\varepsilon_m}{c} \int_{x=0}^{x_0} \left(c^2 - \frac{t^2}{4}\frac{x}{x_0} - c^2 \frac{x^2}{x_0^2} + \frac{t^2}{4}\frac{x^3}{x_0^3}\right) dx$$

$$= 4\sigma_y \frac{\varepsilon_m}{t} \left(\frac{t^2}{4} x - \frac{t^2}{4}\frac{x^2}{2x_0} - \frac{t^2}{4}\frac{x^3}{3x_0^2} + \frac{t^2}{4}\frac{x^4}{4x_0^3}\right)_0^{x_0}$$

$$= \sigma_y \varepsilon_m t \left(x_0 - \frac{x_0}{2} - \frac{x_0}{3} + \frac{x_0}{4}\right)$$

$$= \sigma_y \varepsilon_m t \left(\frac{5}{12} x_0\right), \quad x_0 = 0.060L$$

$$\mathcal{E} = \sigma_y \varepsilon_m t \frac{5}{12} 0.060L$$

$$\mathcal{E} = 0.0250 \, \sigma_y \varepsilon_m t L$$

EVALUATE MAXIMUM STRAIN

$$WORK = W = 0.392\ \sigma_y t^2$$

$$ENERGY = \xi = 0.0250\ \sigma_y\ \varepsilon_m t L$$

$$L = 1.414\ \frac{D}{2} = 0.707\ D$$

$$W = \xi = 0.392\ \sigma_y t^2 = 0.0250\ \sigma_y\ \varepsilon_m t\ 0.707 D$$

$$\varepsilon_m = 22.1\ \frac{t}{D}$$

FOR PIPELINE, $\varepsilon_2 = 0.5\ \varepsilon_1$, $\frac{\varepsilon_3}{\varepsilon_1} \approx 0$

VON MISES: $(\varepsilon_1 - 0.5\varepsilon_1)^2 + (0.5\varepsilon_1 - 0)^2 + (0 - \varepsilon_1)^2 = 4.50\ \varepsilon_{yu}^2 = 1.5\ \varepsilon_1^2$

$$\Rightarrow \varepsilon_{yu} = \sqrt{\frac{1.5}{4.5}}\ \varepsilon_1 = 0.577\ \varepsilon_1 = 0.577\ \varepsilon_m$$

THEREFORE EQUIVALENT UNIAXIAL MINIMUM ULTIMATE ELONGATION IS:

$$\varepsilon_{yu} = 0.577\ (22.1)\ \frac{t}{D} = 12.75\ \frac{t}{D}$$

EXAMPLE 1: $D = 36$, $t = 0.866$, $\frac{D}{t} = 41.5$, $\varepsilon_{yu} = \frac{12.75}{41.5} = 0.307 = 30.7\%$
FLAGGS LINE

EXAMPLE 2: $D = 12.75$, $t = 0.625$, $\frac{D}{t} = 20.4$, $\varepsilon_{yu} = \frac{12.75}{20.4} = 0.625 = 62.5\%$
COGNAC LINE

- CRITICAL / PROPAGATION RATIO

CHART 15-1

$$P_c = \frac{2E}{1-\mu^2}\left(\frac{t}{D}\right)^3 \quad , \quad \frac{D}{t} > 30$$

FOR STEEL, $\mu = 0.28$, $E = 3^{\underline{7}} \Rightarrow \frac{2E}{1-\mu^2} = \frac{2(3^{\underline{7}})}{\underset{.9216}{1-0.28^2}} = 2.170\,(3^{\underline{7}}) = 6.51^{\underline{7}}$

$$\frac{P_c}{P_p} = \frac{6.51^{\underline{7}}\left(\frac{t}{D}\right)^3}{\pi\,\sigma\,\frac{t^2}{D^2}} = \frac{2.07^{\underline{7}}}{\sigma}\,\frac{t}{D}$$

IF GRADE 42, $\sigma_y = 42^{\underline{3}}$:

$$\frac{P_c}{P_p} = \frac{2.07^{\underline{7}}}{42^{\underline{3}}}\,\frac{t}{D} = 4.93^{\underline{2}}\,\frac{t}{D}$$

IF $\frac{D}{t} = 30$, $\frac{P_c}{P_p} = \frac{4.93^{\underline{2}}}{30} = 0.164^{\underline{2}} = 16.4$

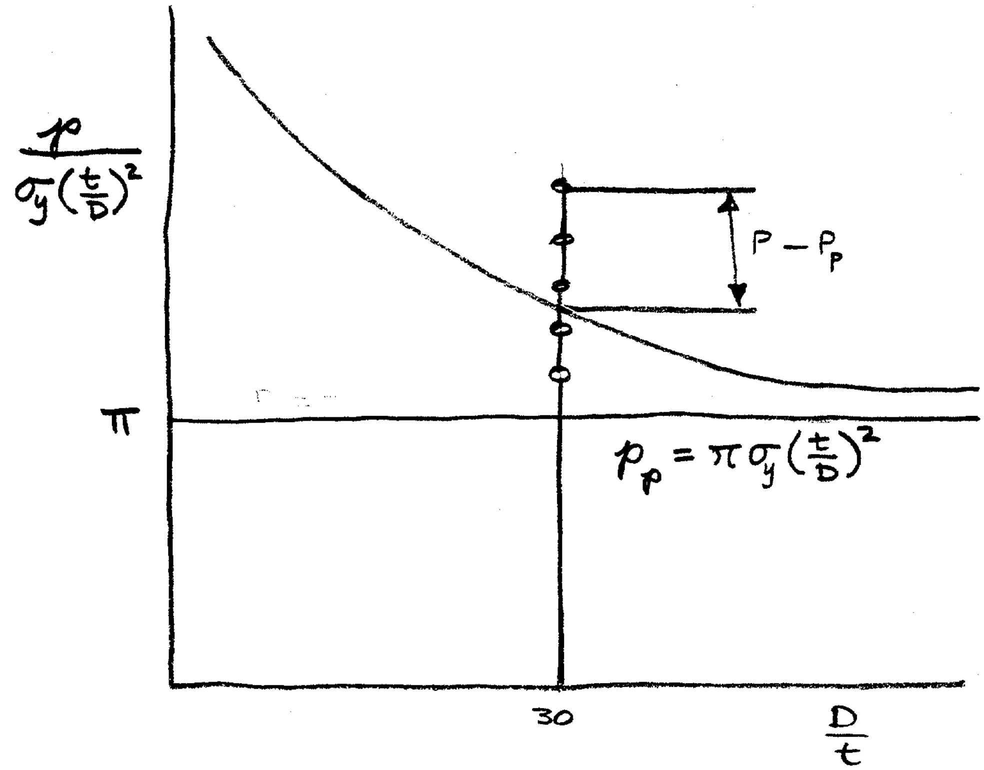
BUT IN PRACTICE , $\frac{P_c}{P_p} = \sim 5-7$

REGARDLESS, $P_p < P_c$

IF $\sigma_y = 60$, $\frac{D}{t} = 41.5$, $\frac{P_c}{P_p} = 8.31$

$\sigma_y = 46$, $\frac{D}{t} = 20.4$, $\frac{P_c}{P_p} = 22.1$

• BUCKLE DRIVING FORCE



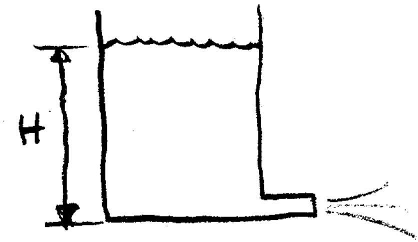
• BUCKLE PROPAGATION VELOCITY

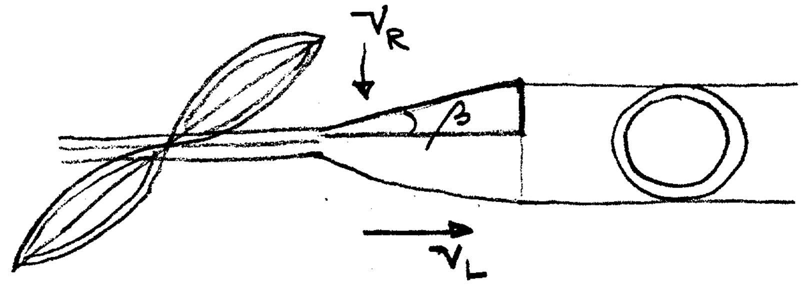
$$V_R = \sqrt{2gH}$$

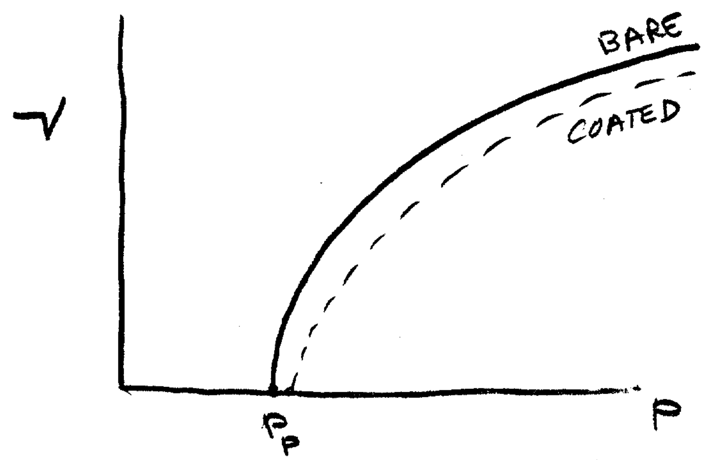
$$H = \frac{\Delta P}{\gamma} = \frac{P - P_p}{\gamma}$$

$$V_R = \sqrt{\frac{2g}{\gamma}(P - P_p)}$$

$$\tan\beta = \frac{V_R}{V_L} \approx \frac{1}{3} - \frac{1}{6}$$







ARRESTOR TYPES/SEQUENCE

CHART 15-4

$P_w = \gamma H$

$P_p < P_c$

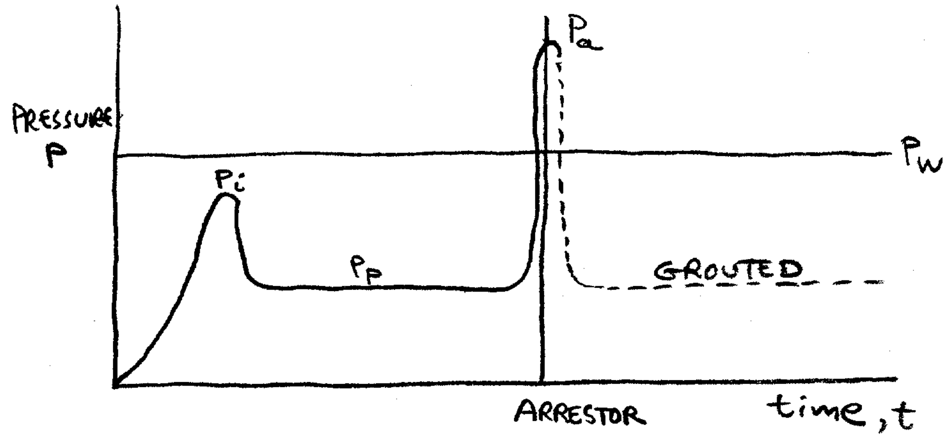
$P_p < P_w$ BY MECHANICS

$P_p < P_i$ DUE TO CONCRETE

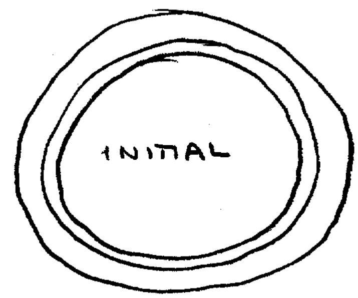
$P_i < P_c$ DUE TO OVALITY

$P_W < P_c$ BY DESIGN

$P_W < P_a$ BY DESIGN

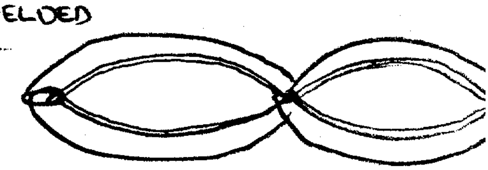


$P_a > P_c$



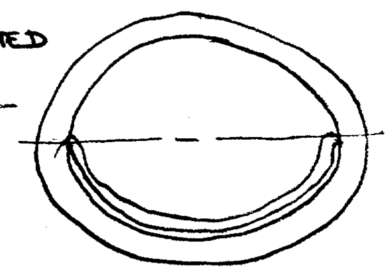
WELDED

$P_a \approx P_c$



GROUTED

$P_a < \sim 4\, P_p$



$$P_p = \pi\, \sigma_{YP} \left(\frac{t}{D}\right)^2$$

$$P_a = \pi\, \sigma_{Ya} \left(\frac{h}{D}\right)^2$$